Ground-based Gamma-ray Astronomy

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OUTLINE

1. Gamma rays
2. Gamma-ray Astrophysics
3. Extensive Air Showers
4. Cherenkov Radiation
5. First Generation VHE Telescopes
6. The Imaging Atmospheric Cherenkov Technique
7. Anatomy of an IAC Telescope
8. Terminology
9. Second Generation Telescopes
10. Third Generation Telescopes
11. TeVCat - status of the TeV sky

Gamma rays

- 1/11 -

Gamma rays ... intro (1/3)

the most energetic radiation (takes up 1/2 EM spectrum)

non-thermal origin

production - nuclear & non-nuclear

detection / interaction ... energy dependent

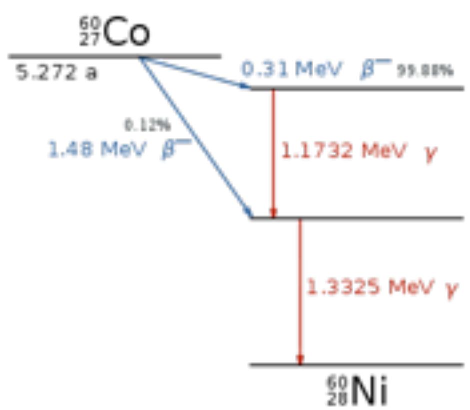
cannot be focused, imaged

neutral => point back to point of origin

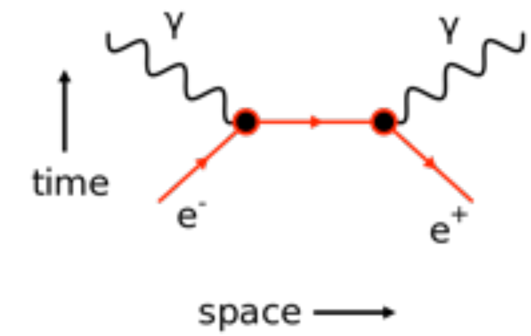
Gamma-rays - production ... intro (2/3)

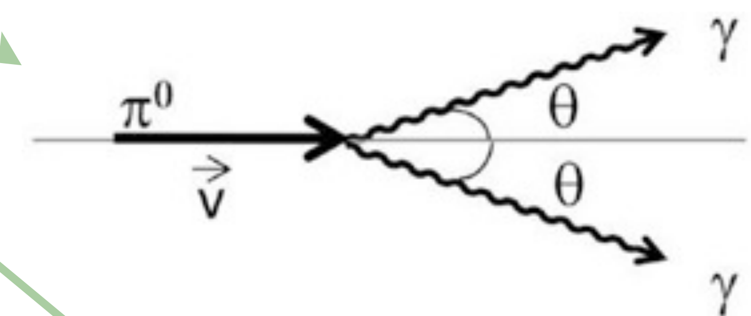
Nuclear & Non-nuclear

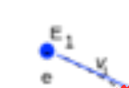
- nuclear decay

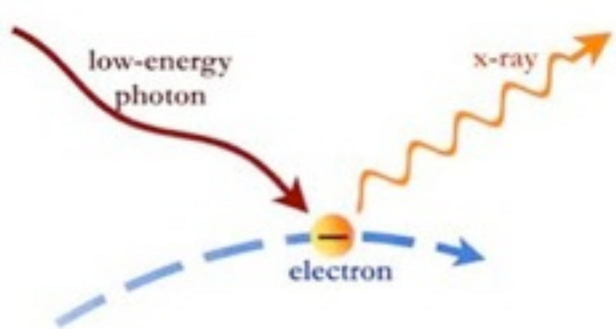


- electron-positron annihilation
- neutral pion decay
- bremsstrahlung / synchrotron
- inverse Compton scattering







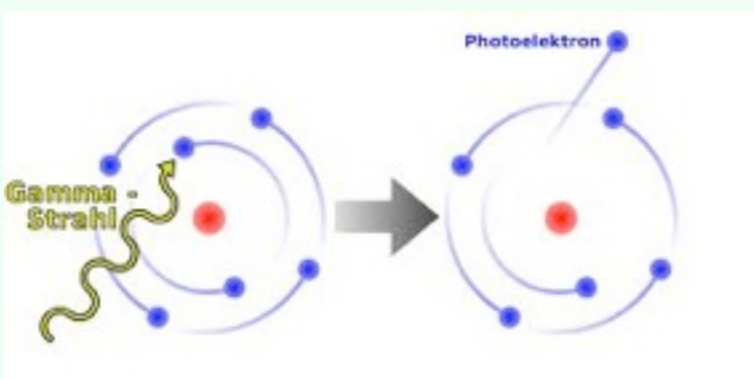


Lots more details in Lucasz's talk

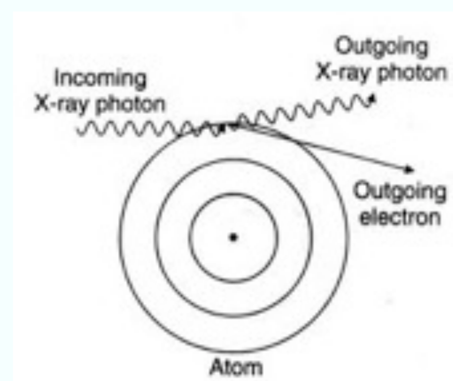
Gamma-rays - detection ... intro (3/3)

- gamma rays ionize matter when they pass through it
- the most likely way that a gamma ray will interact with matter depends on its energy

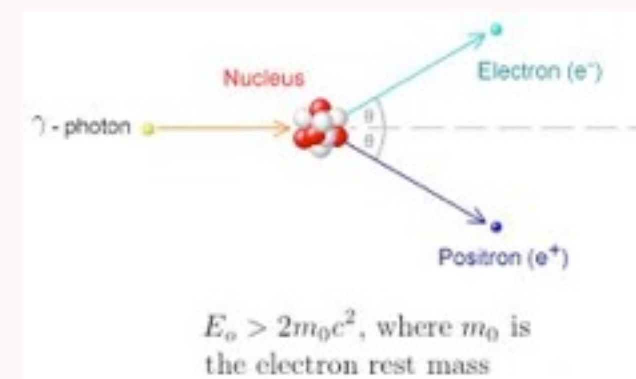
Photoelectric Effect

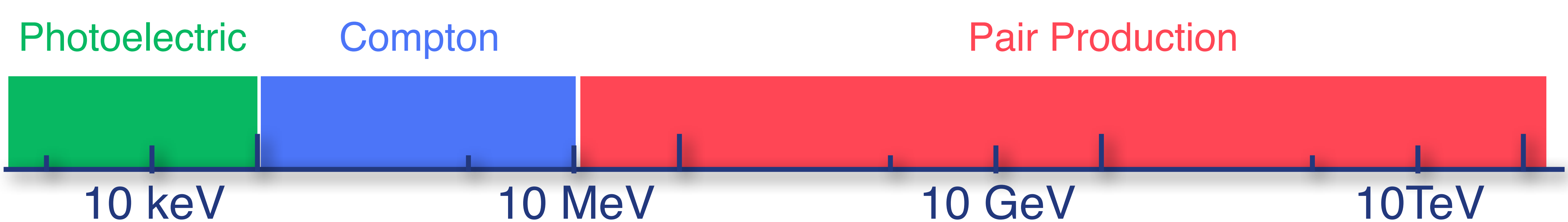


Compton Scattering



Pair Production





Gamma-ray Astrophysics
2/11

Gamma-ray Astrophysics

1. the most energetic radiation (takes up 1/2 EM spectrum)
2. non-thermal origin
3. production - nuclear & non-nuclear
4. detection / interaction ... energy dependent
5. cannot be focused, imaged
6. neutral => point back to point of origin

Gamma-ray Astrophysics 1/6

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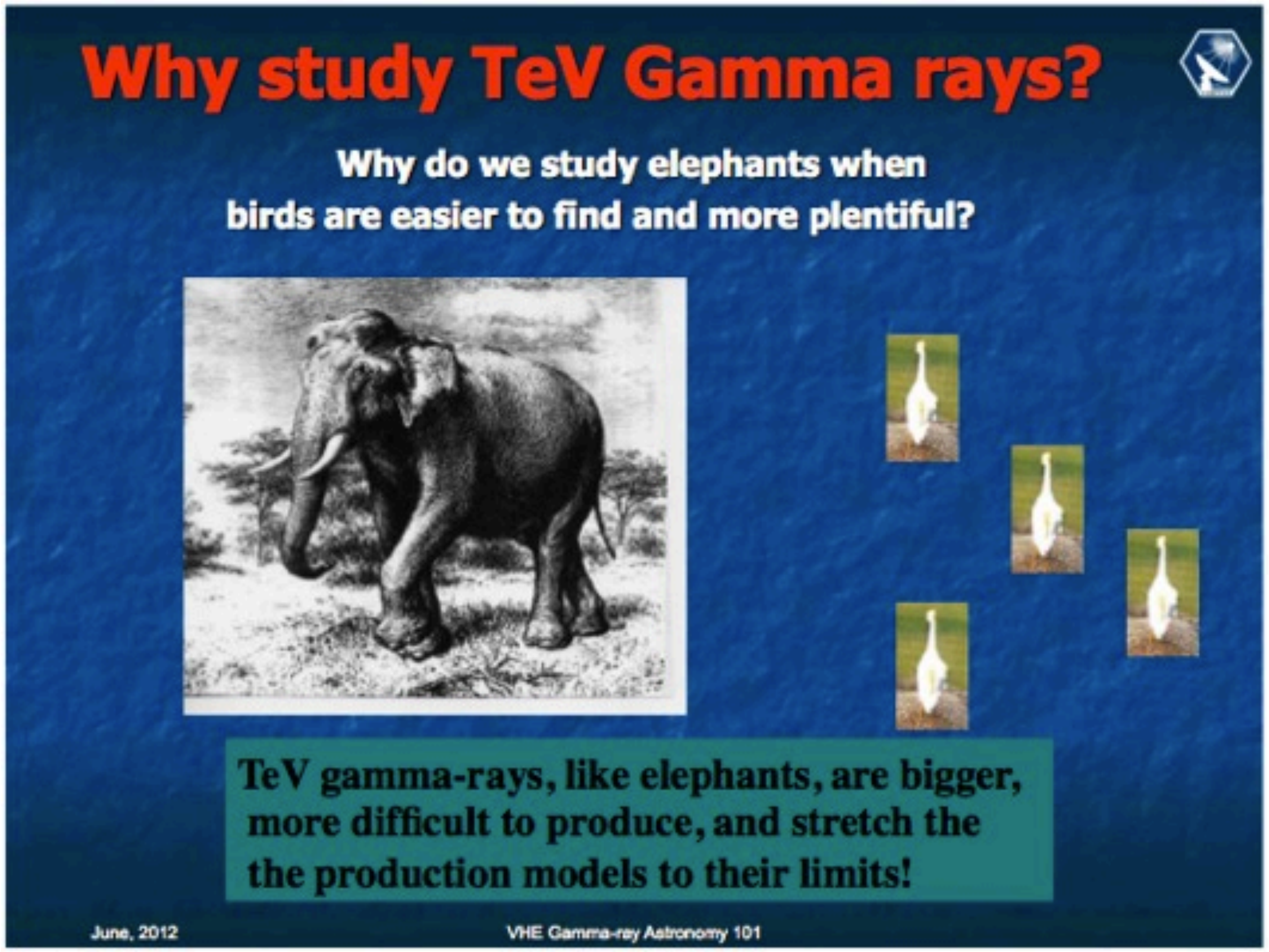
the most energetic radiation
(takes up 1/2 EM spectrum)

Trevor Weekes (Fermi Summer School 2012)



Gamma-ray Astrophysics 1/6

Gamma rays come from the most ~~violent~~ interesting?!? regions in our universe

Gamma-ray Astrophysics 2/6

the most energetic radiation (takes up 1/2 EM spectrum)

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non-thermal origin

- all objects emit thermal radiation due to their non-zero temperature
- it is due to the thermal motion of charged particles in matter
- much of the radiation propagating throughout space and incident on Earth is of thermal origin

Gamma-ray Astrophysics 2/6

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"The word non-thermal is used frequently in high energy astrophysics to describe the emission of high energy particles. I find this an unfortunate terminology, since all emission mechanisms are 'thermal' in some sense. The word is conventionally taken to mean 'continuum radiation from particles, the energy spectrum of which is not Maxwellian'. In practice, continuum emission is often referred to as 'non-thermal' if it cannot be accounted for by the spectrum of thermal bremsstrahlung or black-body radiation" - M. S. Longair

Gamma-ray Astrophysics 2/6

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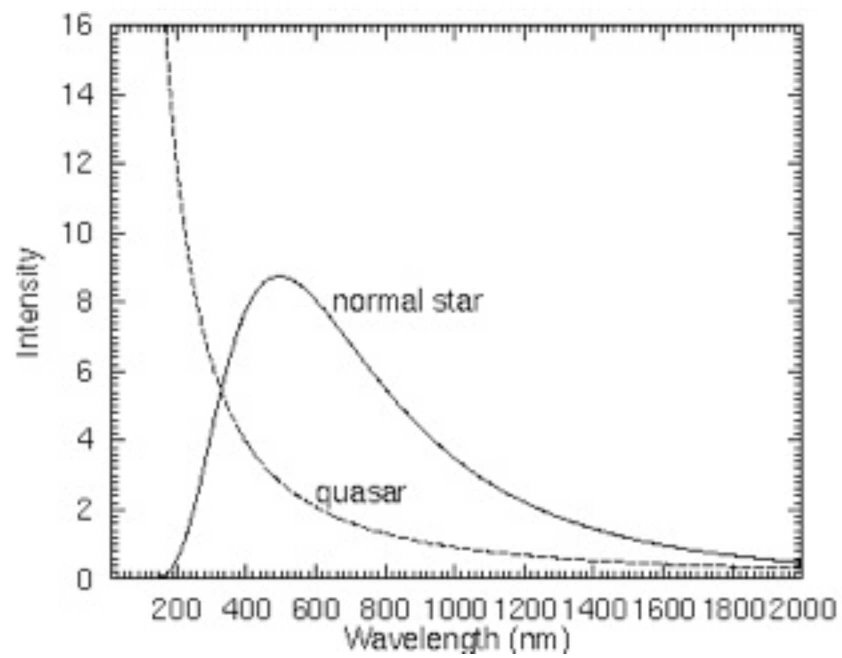
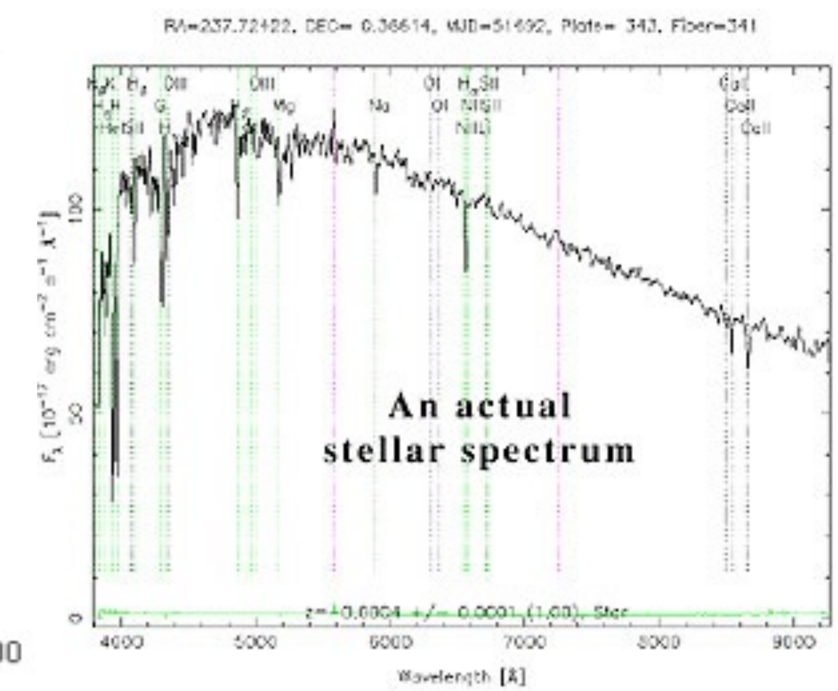
ideal thermal and typical stellar spectra





but...

... it is well known that some particle distributions in the Universe cannot be the result of thermal processes ...

Gamma-ray Astrophysics 2/6

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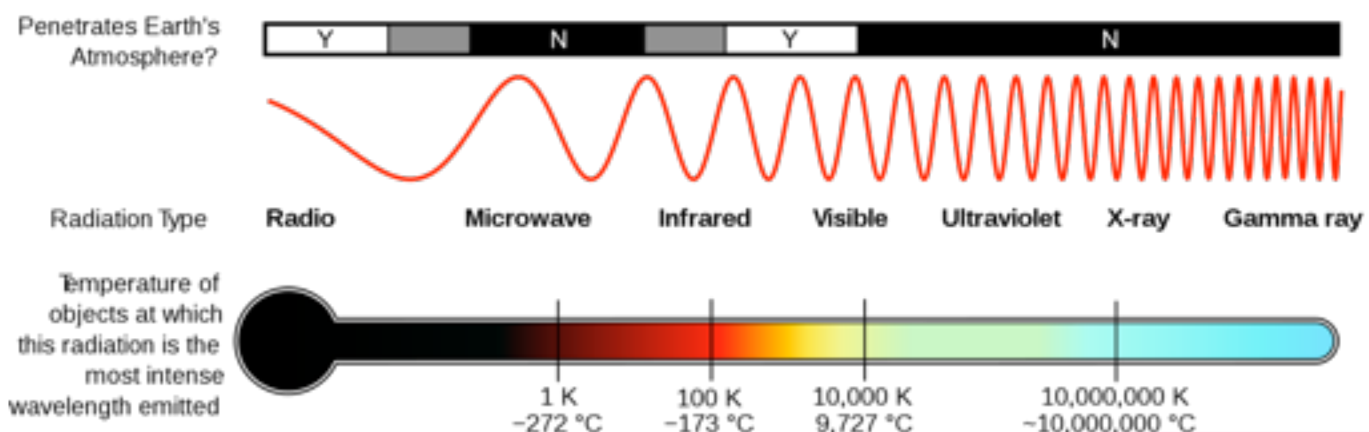
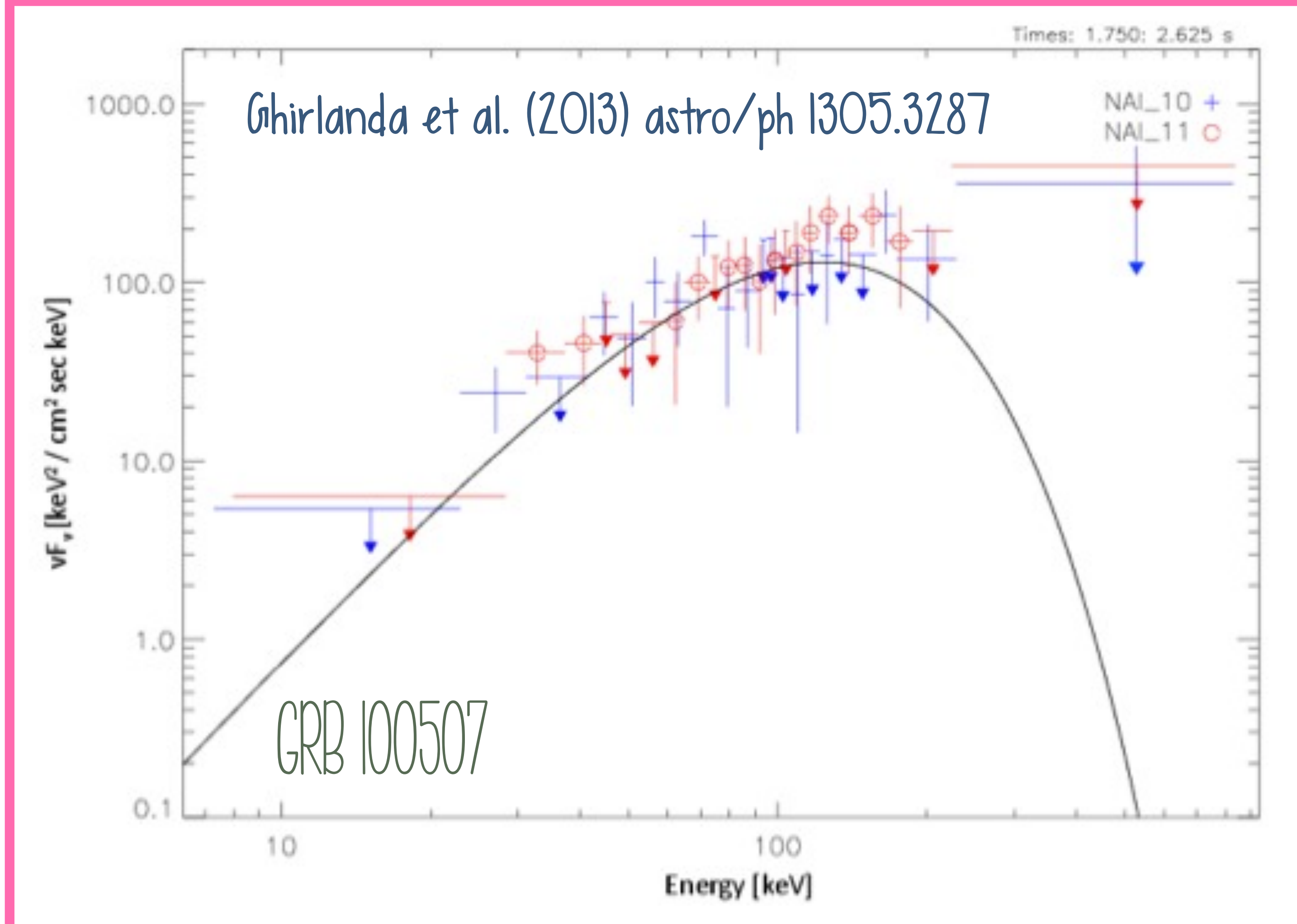
non-thermal origin



under extreme conditions
can get keV thermal emission



Gamma-ray Astrophysics 2/6

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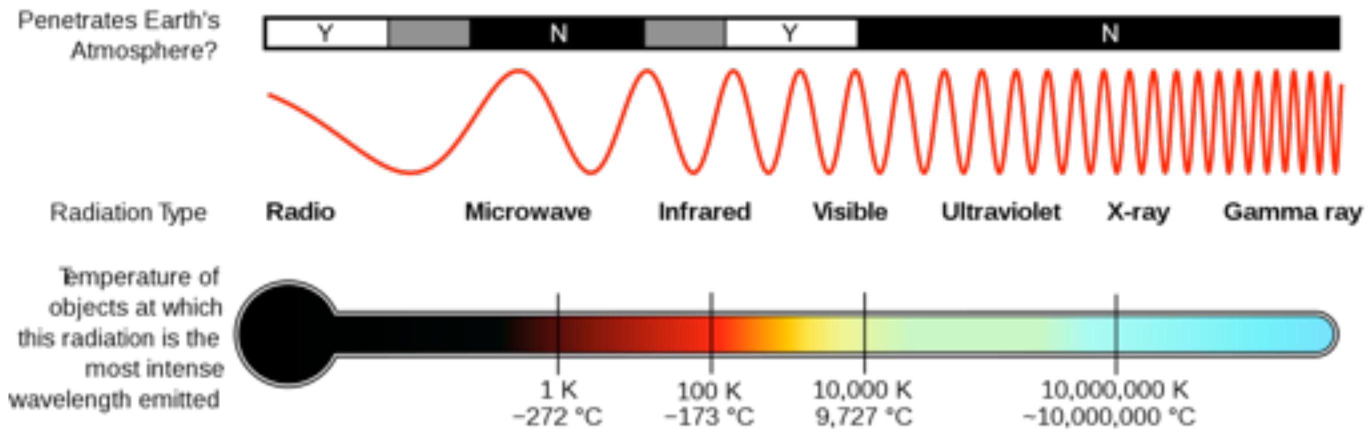

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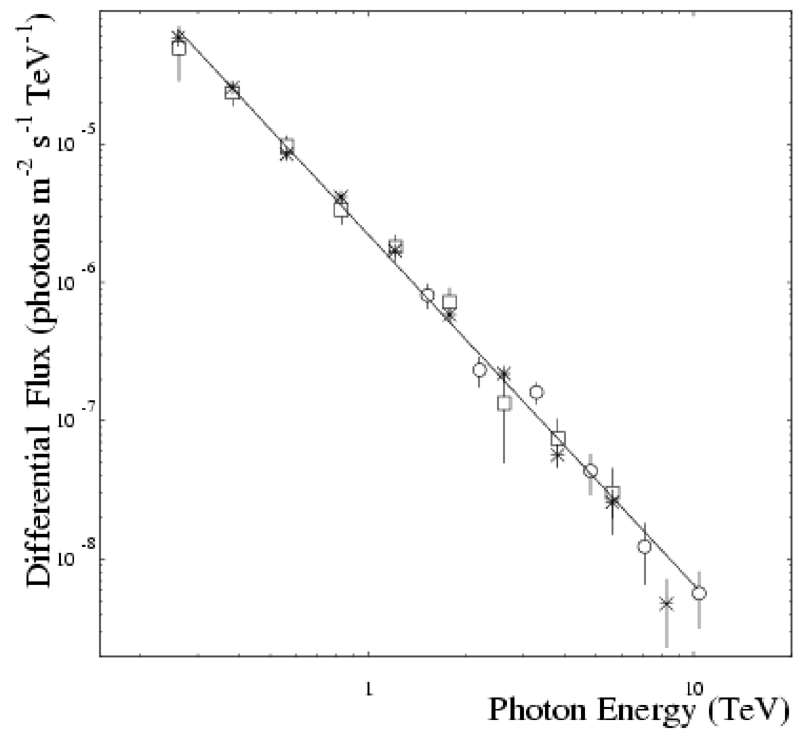

but...

gamma rays are always the result of non-thermal processes ... most of which we do not yet fully understand

POWER-LAW SPECTRA:

$$\frac{dN}{dE}(E) \propto E^{-a}$$

Gamma-ray Astrophysics 3/6

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production

- nuclear & $\boxed{\text{non-nuclear}}$

Hadronic

- neutral pion decay

Electromagnetic

- electron-positron annihilation
- bremsstrahlung/synchrotron*
- inverse Compton scattering

"A difficulty associated with gamma rays is that they can be produced from the interactions of both high-energy protons and electrons. Protons (and nuclei) produce gamma rays through their interaction with target material (e.g. a molecular cloud) and subsequent π^0 decay. Electrons (and positrons) produce gamma rays through the processes of inverse-Compton scattering and bremsstrahlung. Since the gamma rays come from the secondary interactions for both types of primary particles, they trace the combination of the beam (primary particle) density and the target density." - R. A. Ong (2013)

*proton synchroton

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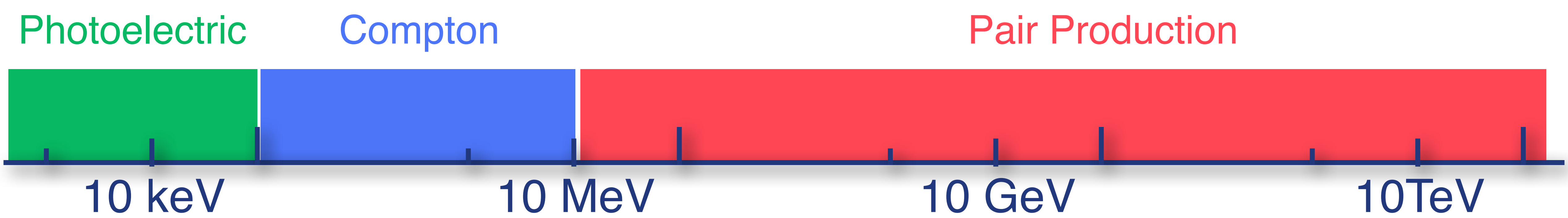

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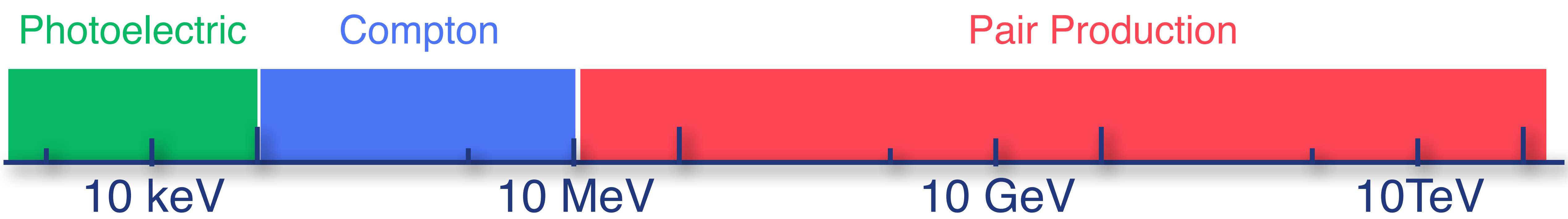

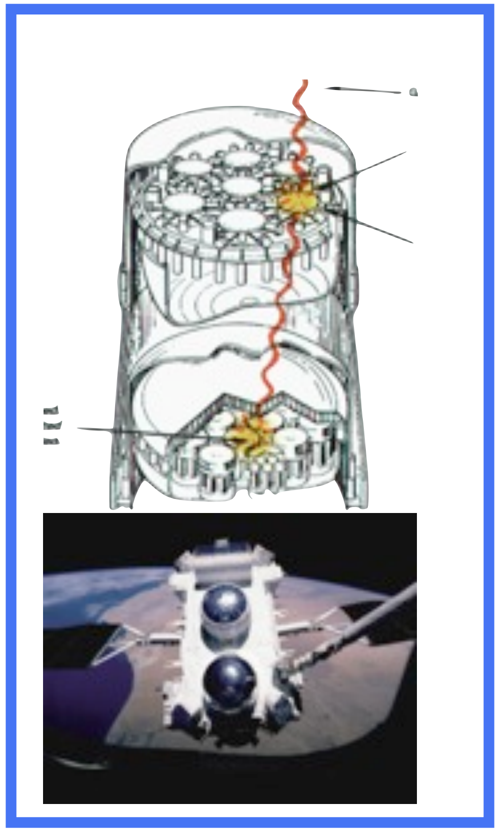

Difficulties with COMPTEL

- higher than expected instrumental background
- angular resolution
- need at least two Compton interactions to occur

Schönfelder & Gottfried (2010), ISSI Scientific Reports Series, ESA/ISSI. ISBN 978-92-9221-938-8, 2010, p. 207-222

Gamma-ray Astrophysics 4/6

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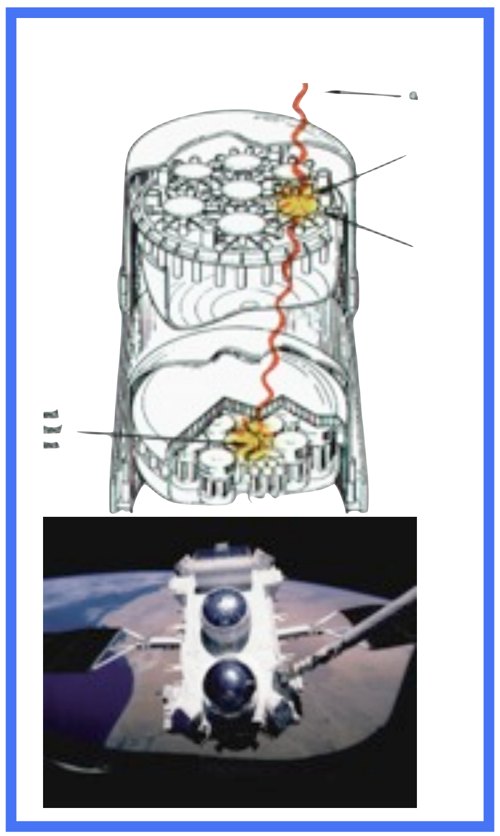

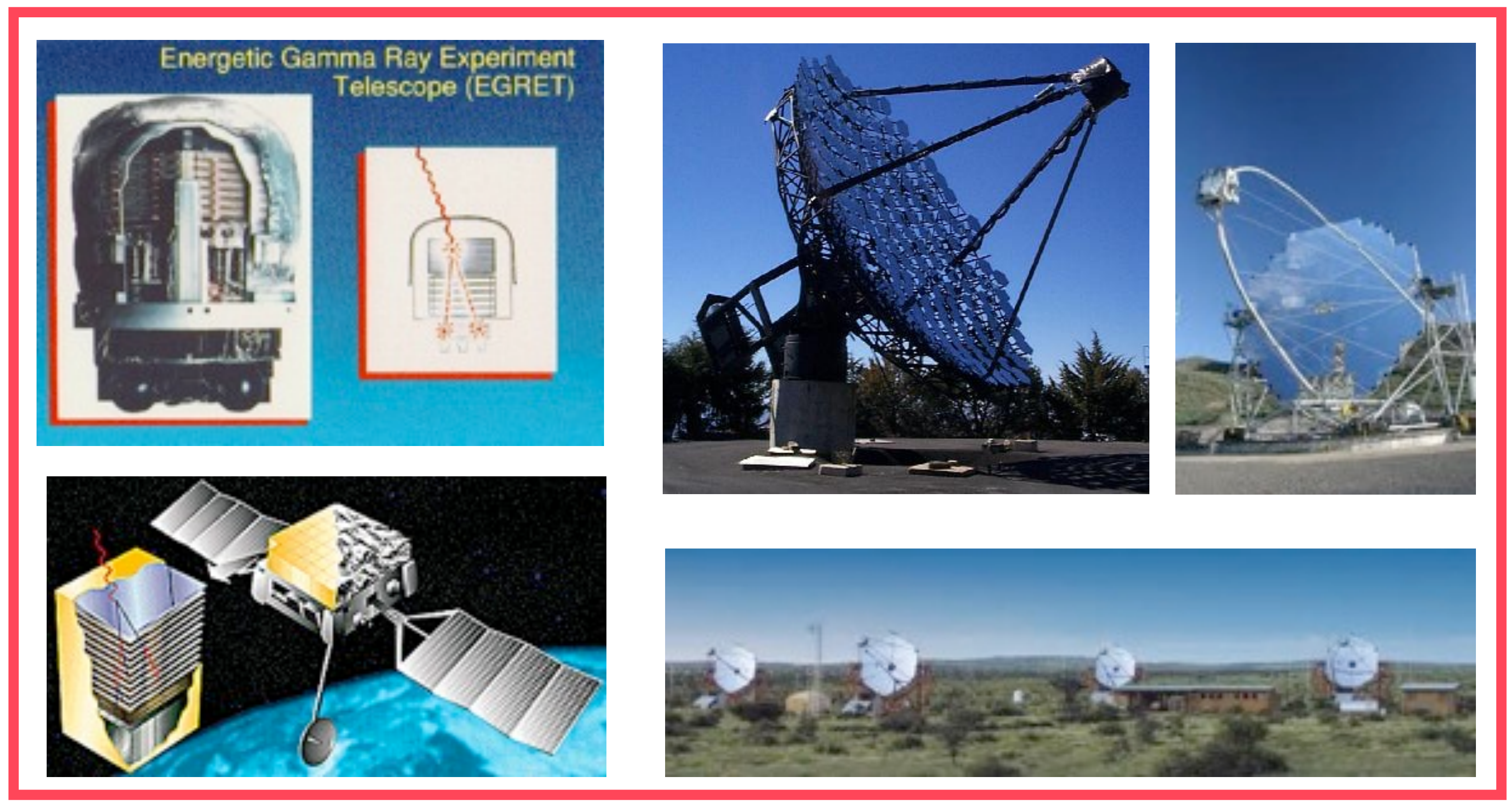

Gamma-ray Astrophysics 4/6

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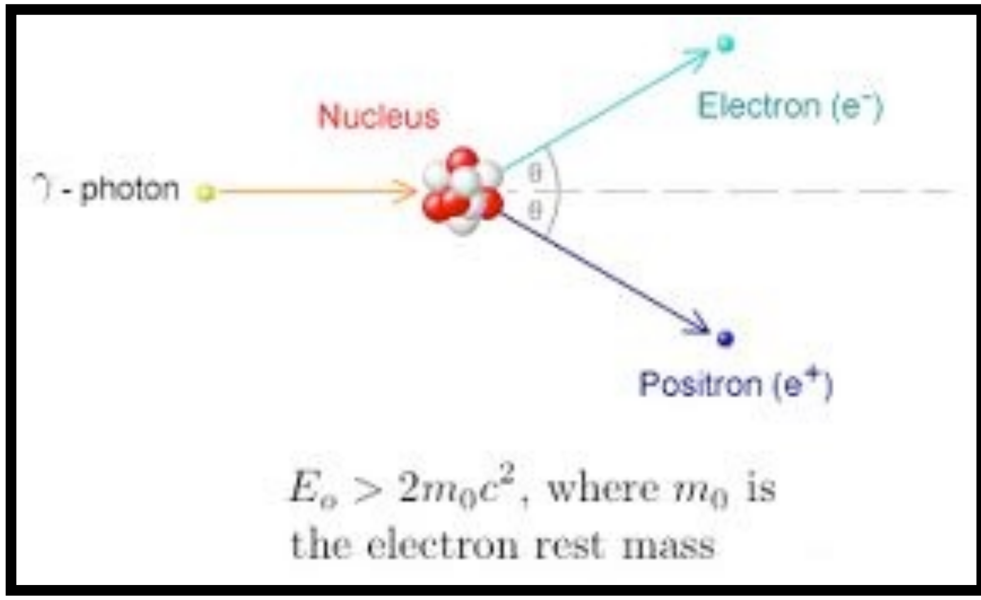

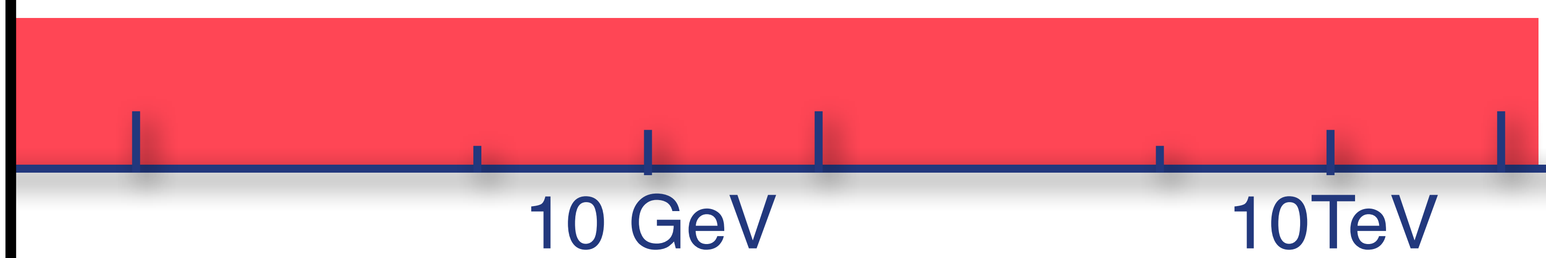

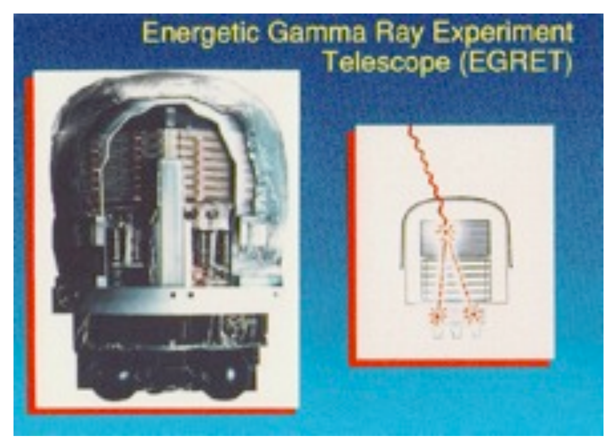

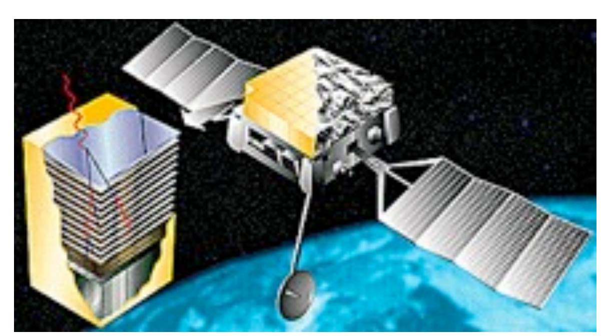

PAIR PRODUCTION

$$\gamma + \gamma^{*} \longrightarrow e^{+}e^{-}$$

* virtual photon in field of nucleus

Gamma-ray Astrophysics 4/6

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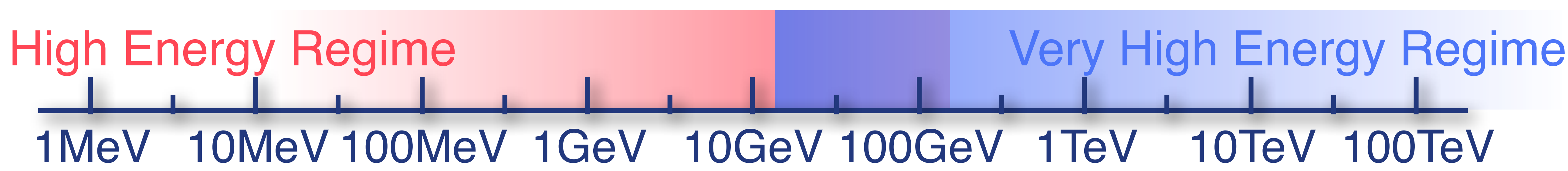
detection / interaction ... energy dependent

the manner in which we use pair production to detect the gamma rays is different ... so we divide gamma-ray astrophysics into "High Energy" (HE) and "Very High Energy"



but, more often than not, the physics at the source is the same:

- complementarity
- independent verification (energy scale)
- multiwavelength observations

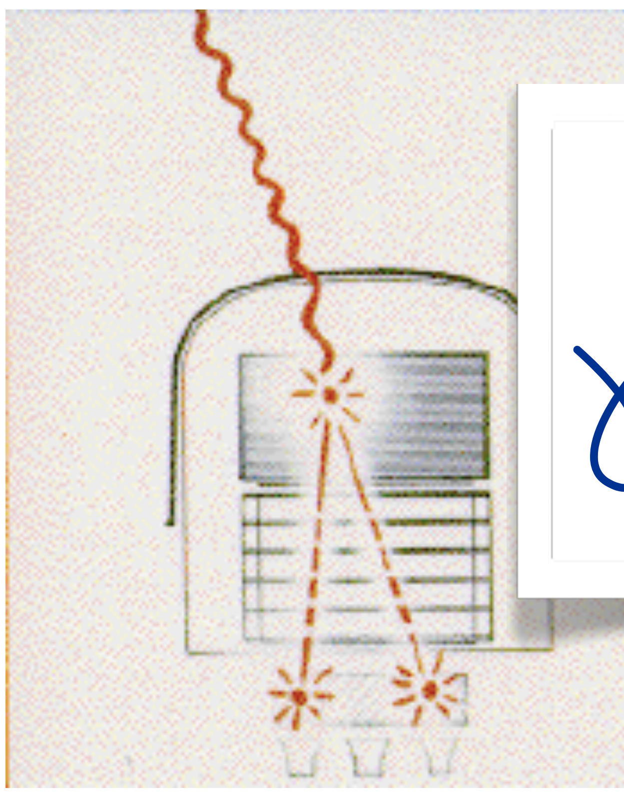
Gamma-ray Astrophysics 4/6

High Energy Regime | Very High Energy Regime

1MeV 10MeV 100MeV 1GeV 10GeV 100GeV 1TeV 10TeV 100TeV

- particle interacts directly in detector
- limited by physical size of detector

- particle interacts in the atmosphere
- large collection area



PAIR PRODUCTION

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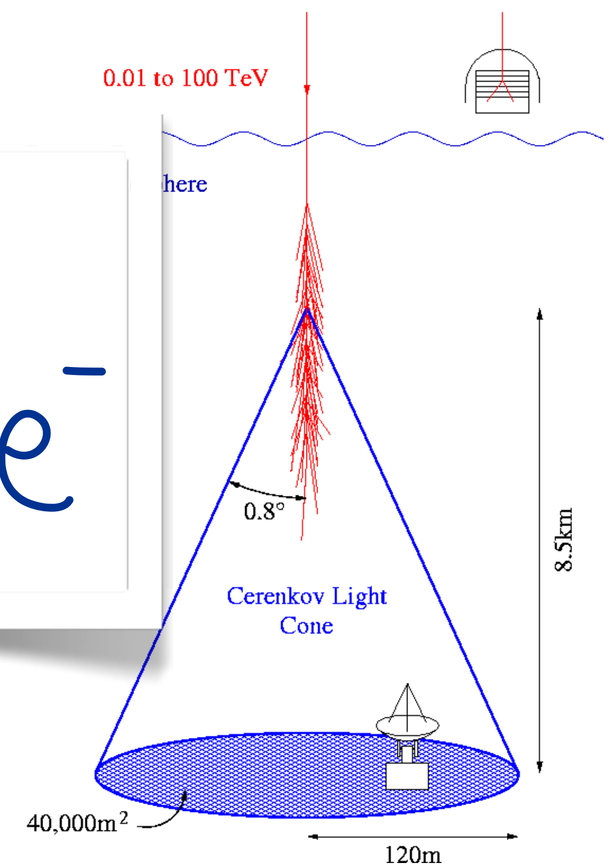

Fermi, EGRET, INTEGRAL ...

Whipple, VERITAS, HESS, MAGIC ...

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detection / interaction
... energy dependent

When a gamma ray passes through a medium, the probability for absorption depends on the properties of that medium:

- its thickness
- its density
- its absorption cross section

And on the energy of the gamma ray

absorption coefficient

$$I(x) = I_0 e^{-\mu x}$$

distance, x

beam intensity after distance, x

initial beam intensity

Gamma-ray Astrophysics 4/6

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When a gamma ray passes through a medium, the probability for absorption depends on the properties of that medium:

- its thickness
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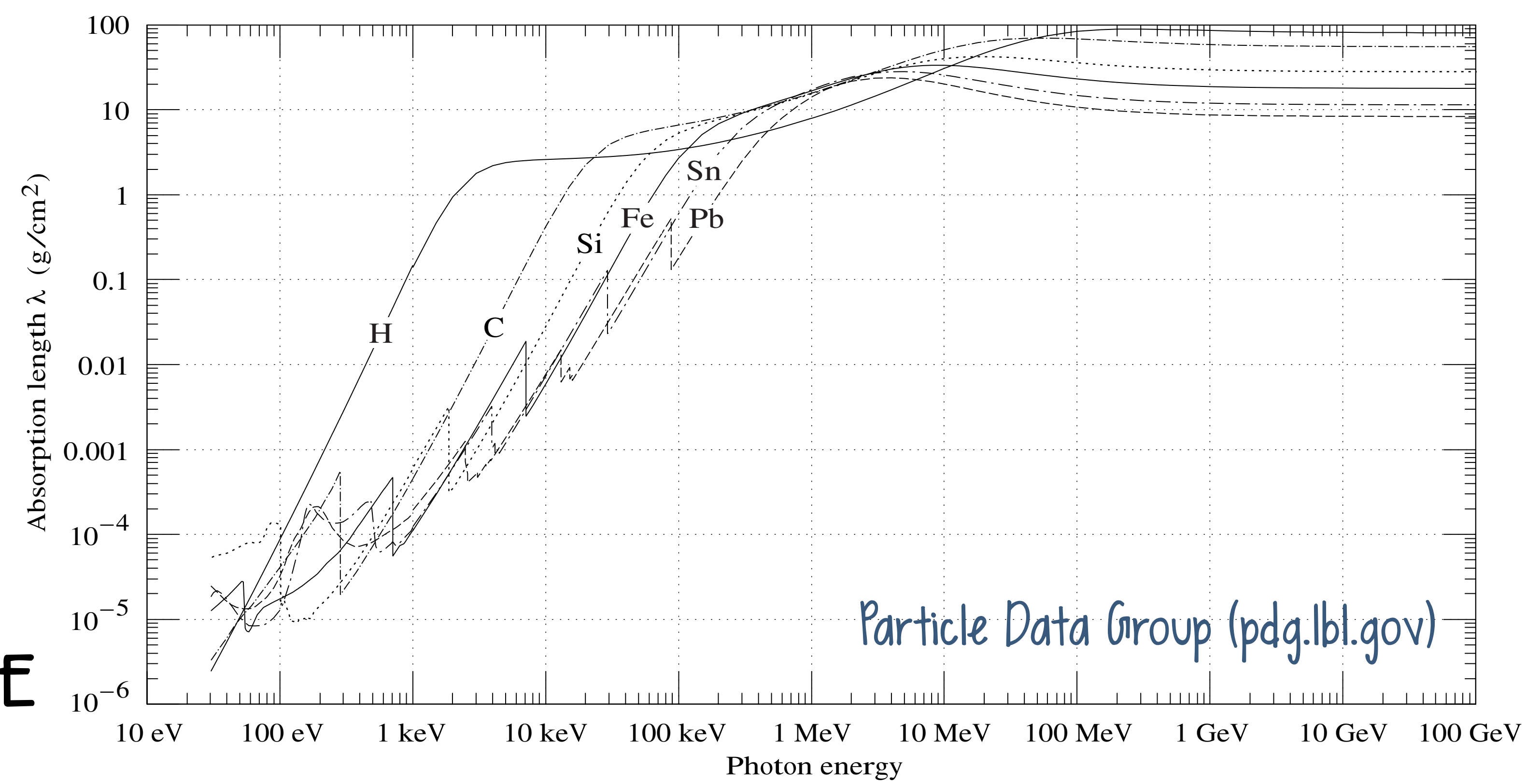
And on the energy of the gamma ray

earth's atmosphere is ~ 1000 $g cm^{-2}$ ... the equivalent of about 1 metre of lead for HE gammas

MEAN FREE PATH



ENERGY

Gamma-ray Astrophysics 5/6

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cannot be focused, imaged

→ therefore: NO OPTICS

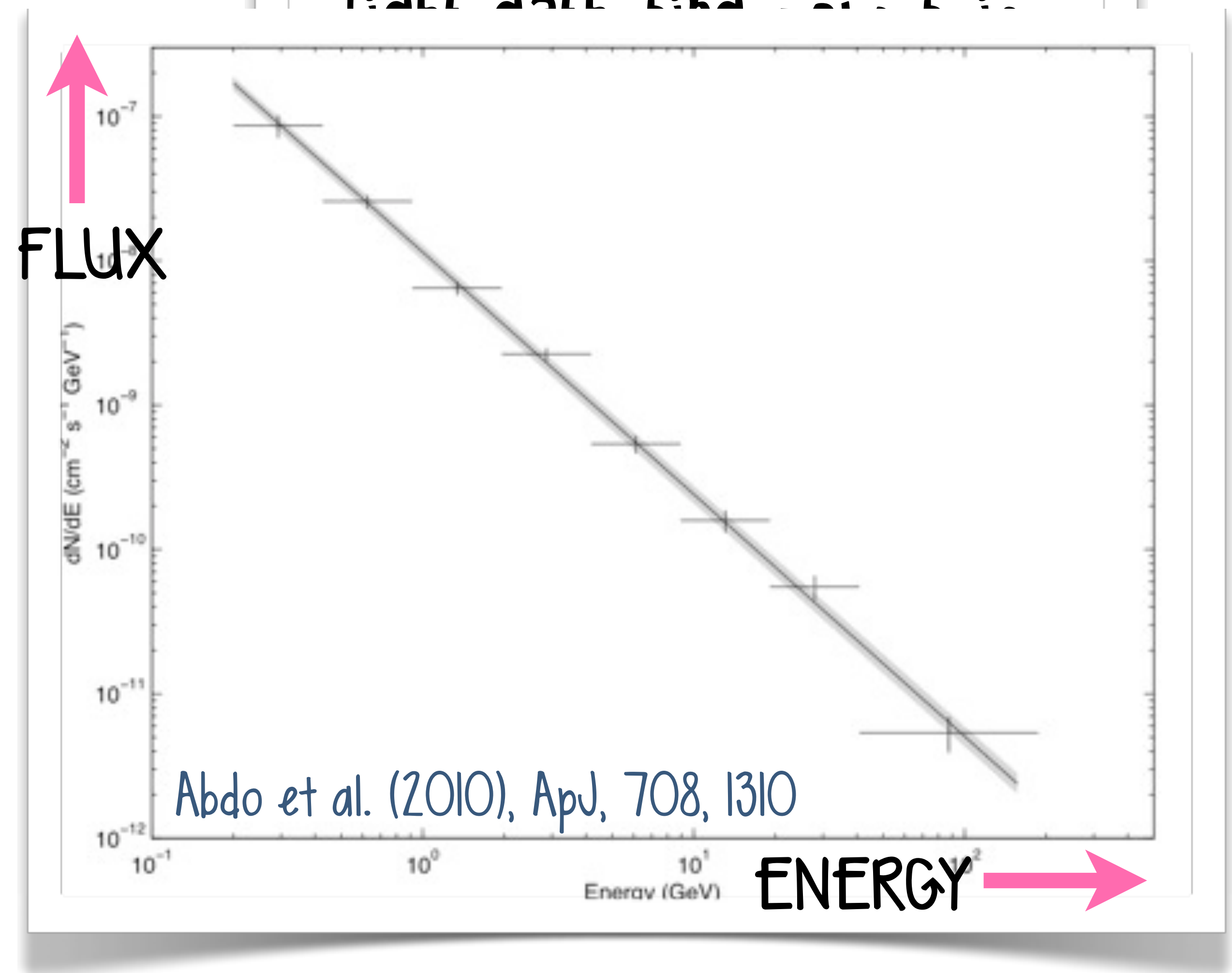
detector area IS the collection area!

→ the photon must pass through your detector system in order for it to be detected

- note -
in an optical telescope, the

and...

gamma-ray flux is distributed as a power law --> falling RAPIDLY with INCREASING ENERGY!



Gamma-ray Astrophysics 6/6

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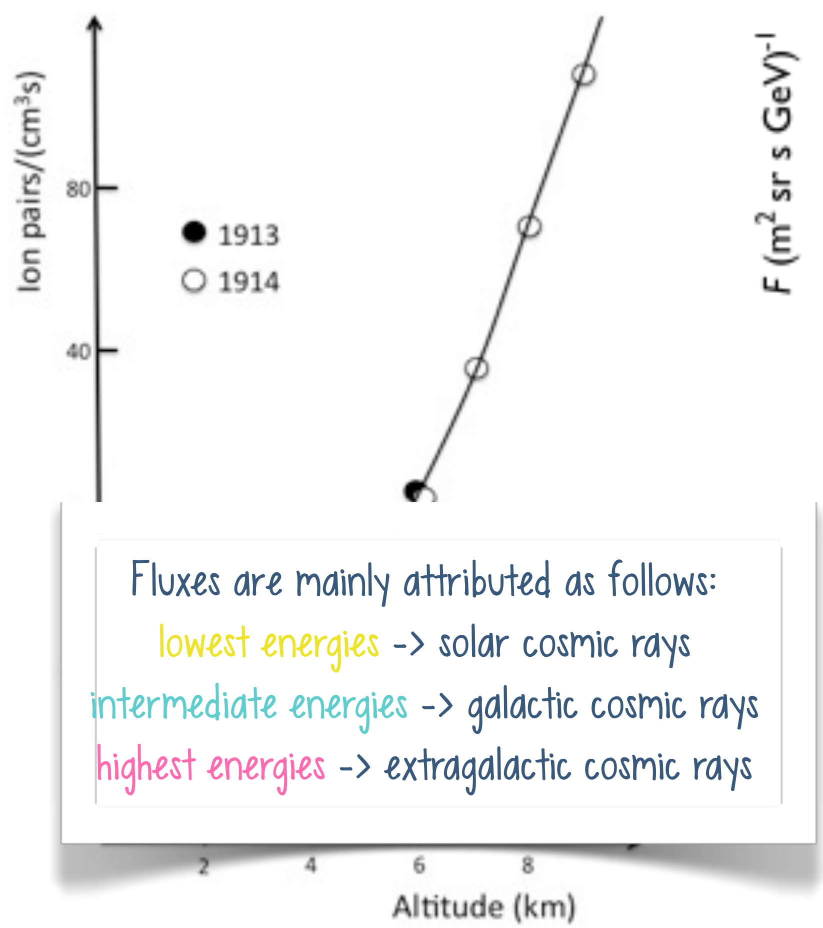
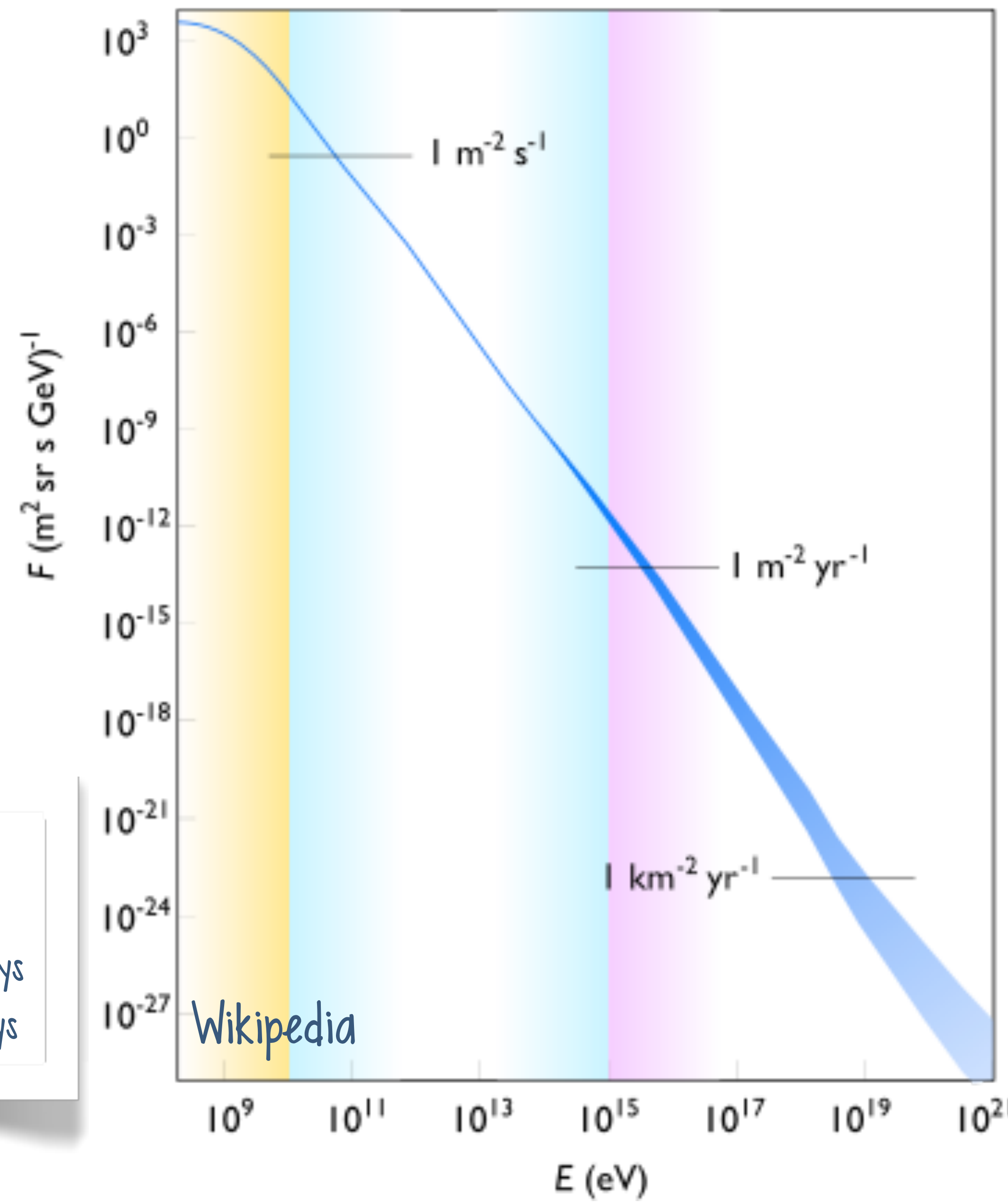
- one of the big motivations for gamma-ray astronomy was (is) the search for the origin of the high-energy cosmic rays
- their origin has been a mystery since their discovery 101 years ago by Victor Hess



Fluxes are mainly attributed as follows:
lowest energies -> solar cosmic rays
intermediate energies -> galactic cosmic rays
highest energies -> extragalactic cosmic rays



Gamma-ray Astrophysics 6/6

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- cosmic rays are charged:
  ... MOSTLY PROTONS
- they do not point back to their point of origin because they get deflected in magnetic fields
- the sites of acceleration of cosmic rays would also be sources of high-energy gamma rays

the ORIGINAL THINKING

- in the early days of gamma-ray physics at very high energies, there were no known sources of TeV gamma rays.
- it was thought that, if such sources were found, they would correspond with the sources of the high-energy cosmic rays
- If an object was capable of accelerating charged particles to such high energies, then it would surely also be a source of TeV gamma rays
- this is still the thinking but we have many sources of TeV gamma rays - it's not clear which of them are sources of the highest energy cosmic rays *(more on that later)*

Gamma-ray Astrophysics 6/6

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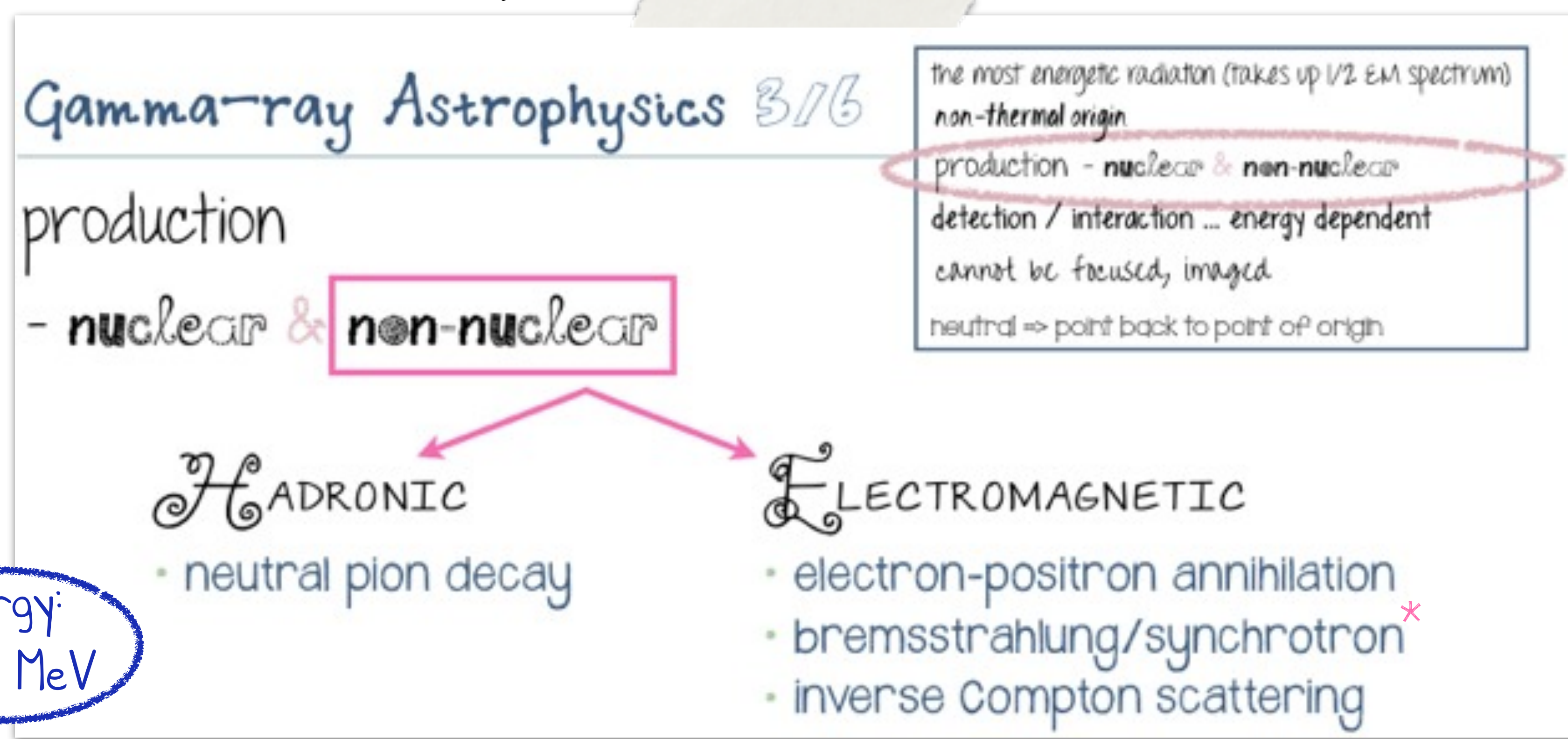
$$p + p \to \pi^0 + X^*$$

$$\pi^0 \xrightarrow{*} \gamma + \gamma$$

* other products

* 98.8% of the time

energy: 67.5 MeV


Gamma-ray Astrophysics 3/6

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production

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HADRONIC
- neutral pion decay

ELECTROMAGNETIC
- electron-positron annihilation
- bremsstrahlung/synchrotron*
- inverse Compton scattering

Gamma-ray Astrophysics 6/6

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SO... IF we could establish the hadronic origin of gamma rays from a class of sources, it would be a strong indication that this was the source of the high-energy cosmic rays

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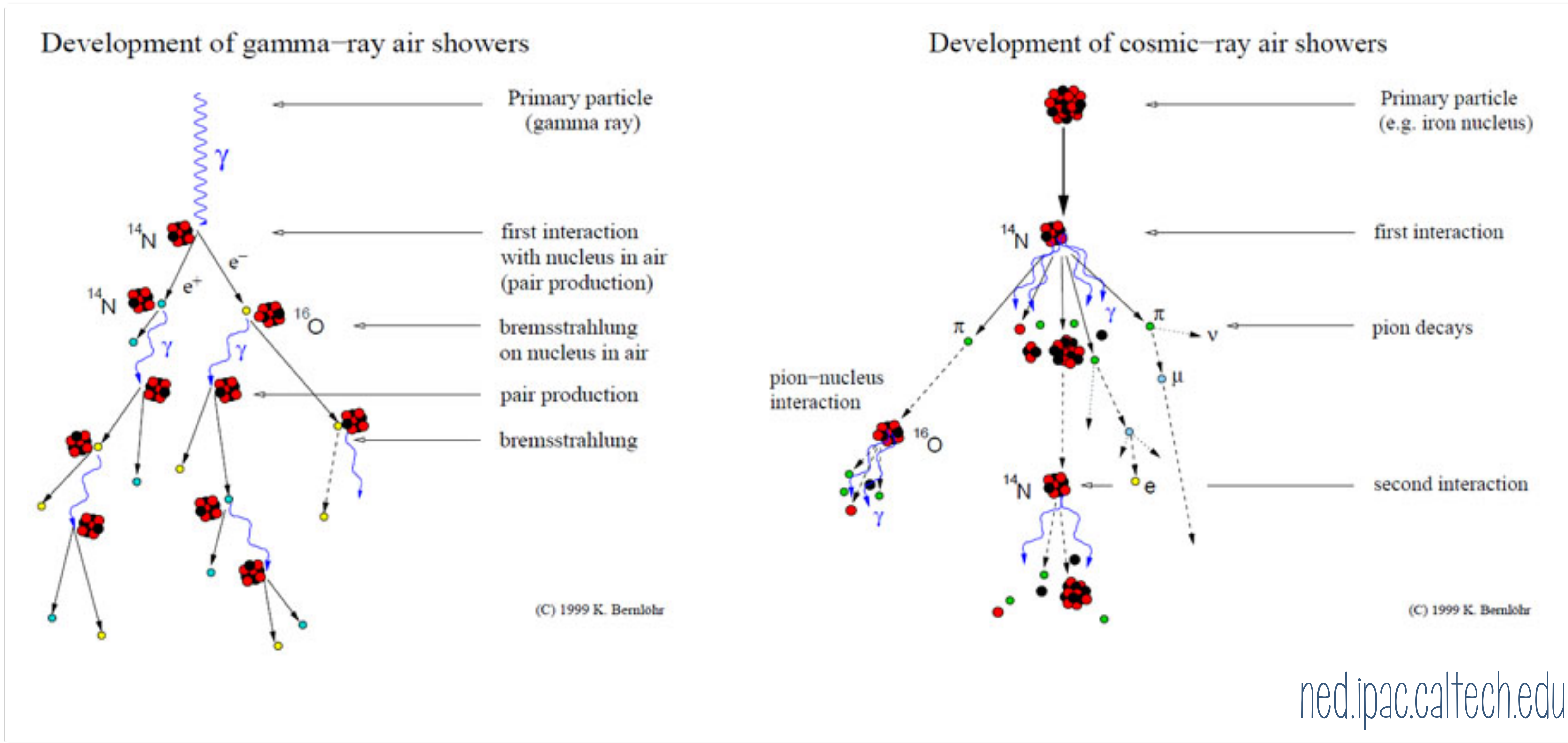
Extensive Air Showers

3/11

Extensive Air Showers (EAS)

When a high-energy proton or gamma ray enters the earth's atmosphere ...



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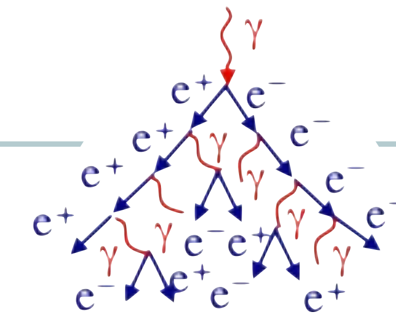
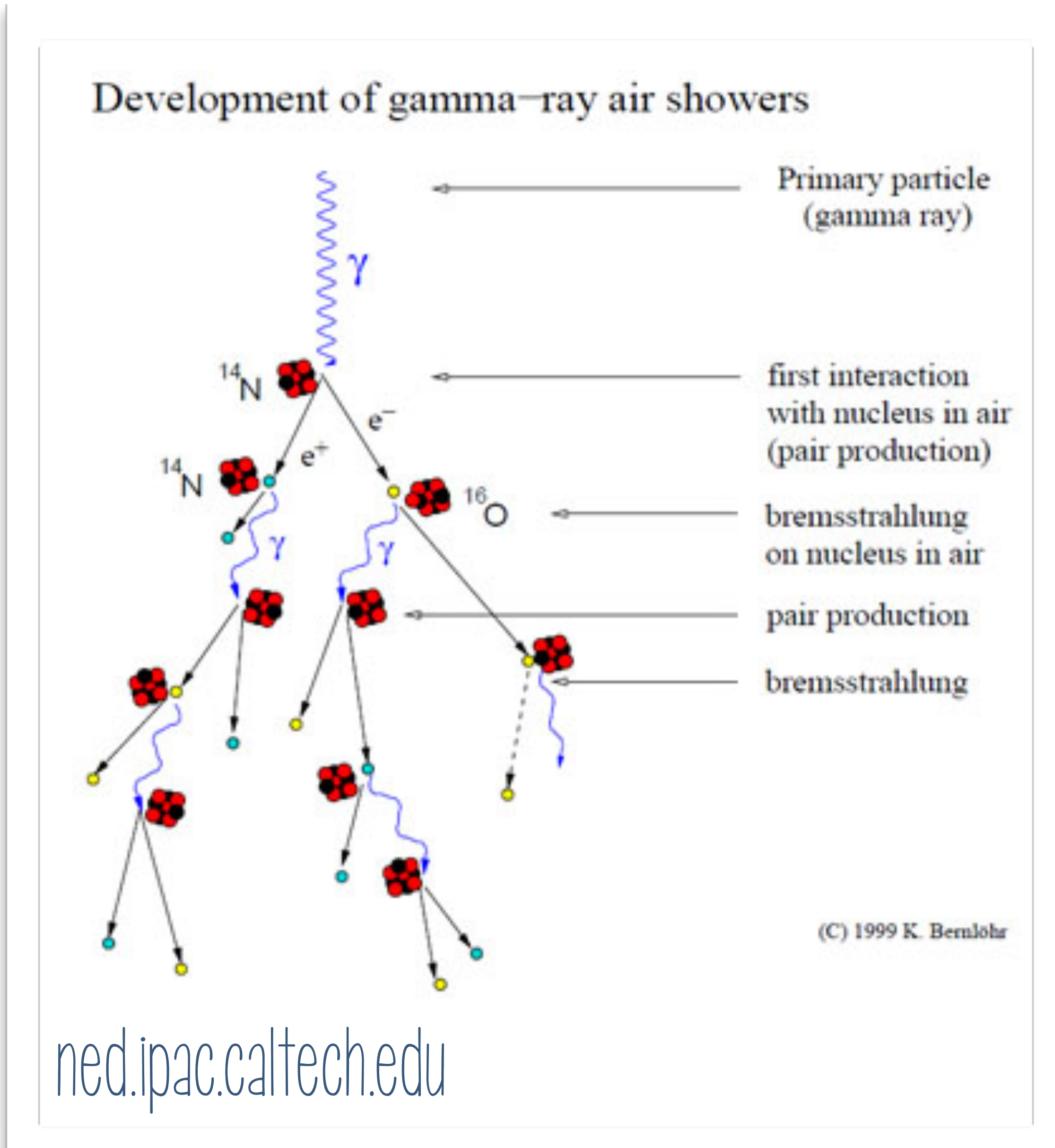


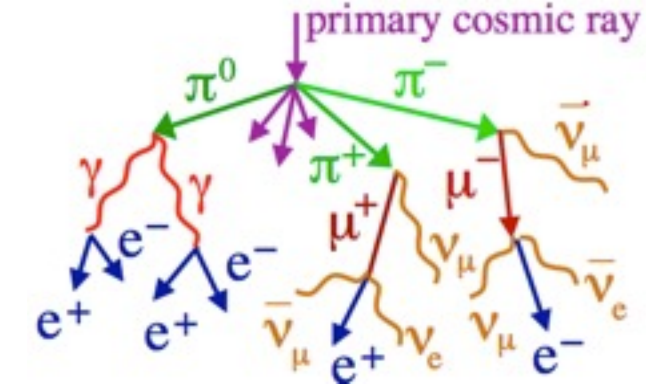
When a high-energy GAMMA RAY enters the earth's atmosphere ...



- **when a high energy gamma ray passes close to an atomic nucleus in the Earth's atmosphere, it pair produces**
  - **radiation length = 37.7 g cm^{-2}**
  - **total atmospheric depth ~1000 g cm^{-2}**
    - ➡ **gamma ray interacts close to the top of the atmosphere**
- e^+e^- pair subsequently undergo bremsstrahlung (similarly high cross-section as pair-production), resulting in the production of a high-energy gamma ray*
- **this cycle of pair-production followed by bremsstrahlung continues, resulting in an exponentially growing cascade of particles and radiation, until shower maximum is reached**
- at this point, the critical energy (84.2 MeV) at which the electrons lose energy equally by radiation and ionization is reached
  - ➡ beyond this stage, the electrons lose energy rapidly by ionization and cascade multiplication ceases with the particles then being absorbed

*Some muons can also be produced from pion production in photonuclear reactions, but the probability for this is low ... about 10^{-4} times that of pair production

Extensive Air Showers (EAS)



When a high-energy PROTON enters the earth's atmosphere ...

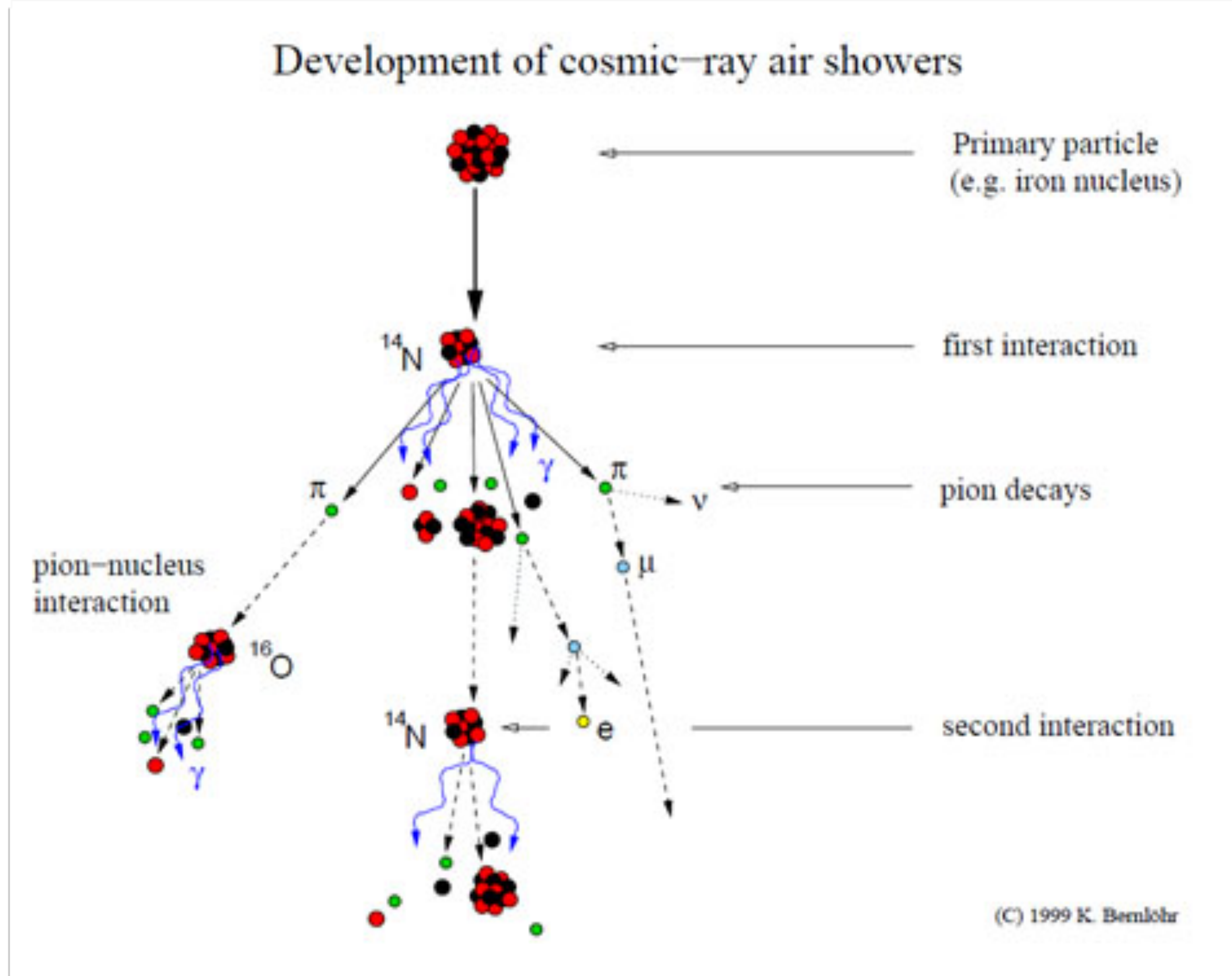
- **most air showers are hadronic**
- when these particles collide with oxygen and nitrogen, cascades of elementary particles and radiation are induced
- **the initial products include nucleons and kaons, but primarily consist of charged and neutral pions which subsequently decay through a number of decay chains**

$\pi^+ \rightarrow \mu^+ + \nu,\ \tau = 2.6 \times 10^{-8}\,s$

$\pi^- \rightarrow \mu^- + \bar{\nu},\ \tau = 2.6 \times 10^{-8}\,s$

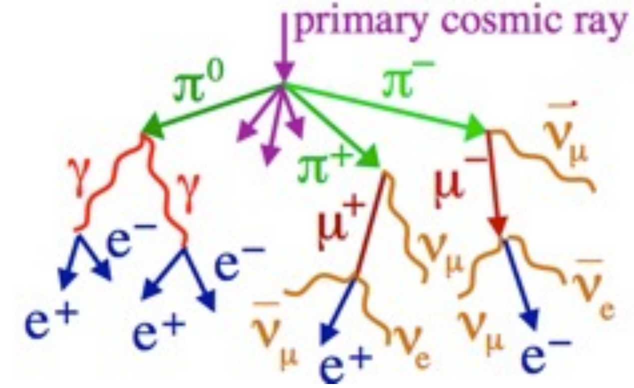
$\pi^0 \rightarrow \gamma + \gamma,\ \tau = 8.4 \times 10^{-17}\,s$

- since muons do not interact strongly, most of those produced penetrate to the Earth's surface.
  - ➡ relativistic effects: their lifetimes are effectively longer in the atmosphere than in their rest frame.
  - ➡ in hadron showers, several percent of the particles reaching the ground are muons



ned.ipac.caltech.edu

Extensive Air Showers (EAS)

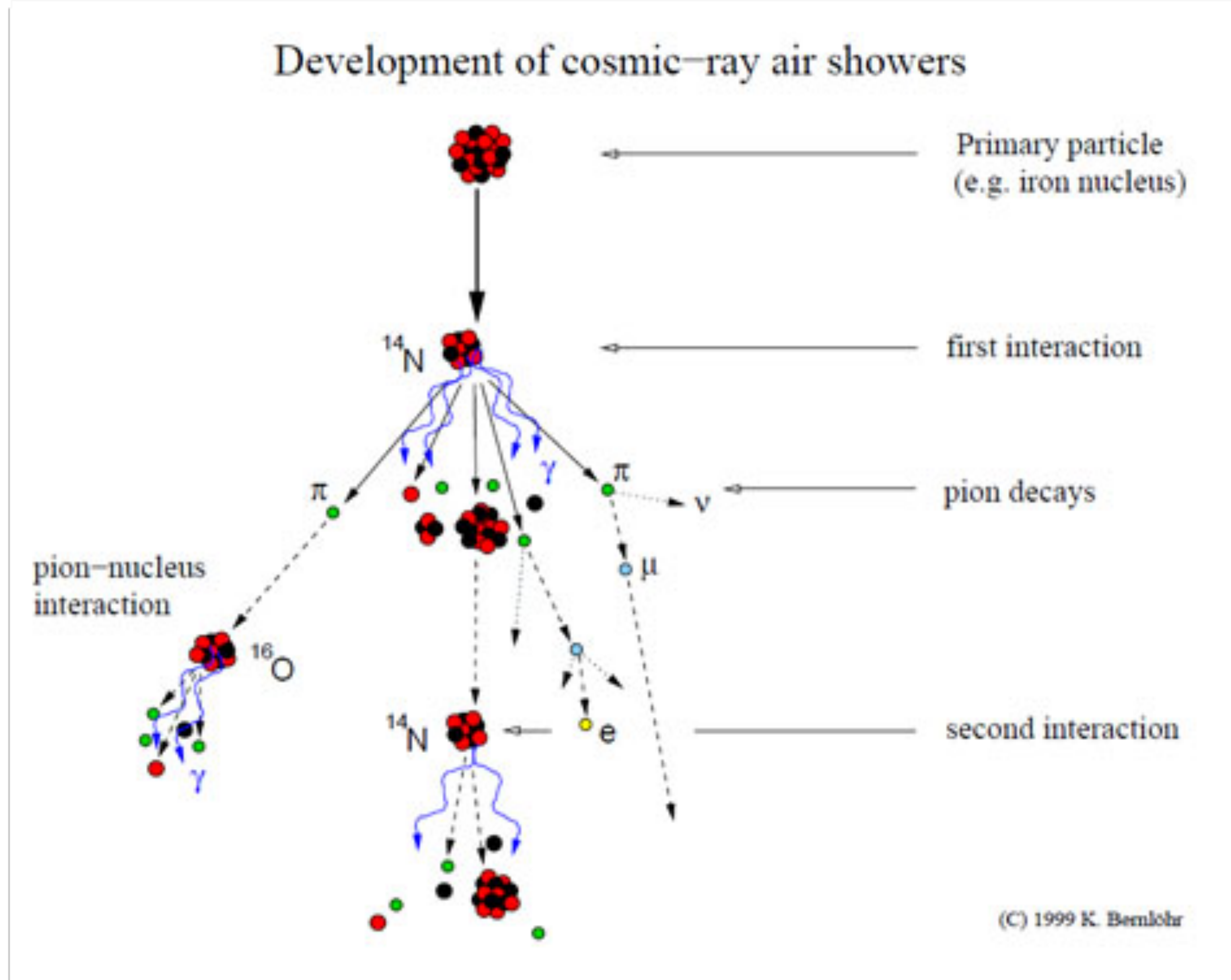


When a high-energy PROTON enters the earth's atmosphere ...

- **most air showers are hadronic**
- when these particles collide with oxygen and nitrogen, cascades of elementary particles and radiation are induced
- **the initial products include nucleons and kaons, but primarily consist of charged and neutral pions which subsequently decay through a number of decay chains**

$$\pi^+ \rightarrow \mu^+ + \nu, \quad \tau = 2.6 \times 10^{-8}\,s$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}, \quad \tau = 2.6 \times 10^{-8}\,s$$
$$\pi^0 \rightarrow \gamma + \gamma, \quad \tau = 8.4 \times 10^{-17}\,s$$

- At each generation of hadronic pion production ~1/3 of the pions are π^0s
  - ➡ immediately decay into two gamma rays (~70MeV)
  - ➡ these subsequently pair produce
  - ➡ electromagnetic cascades rapidly grow to comprise the dominant component within the hadronic cascade



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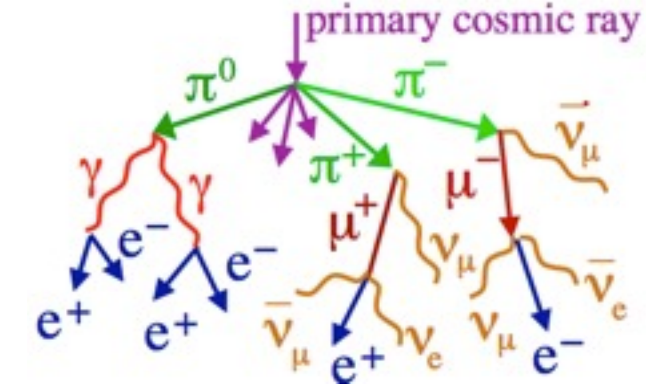
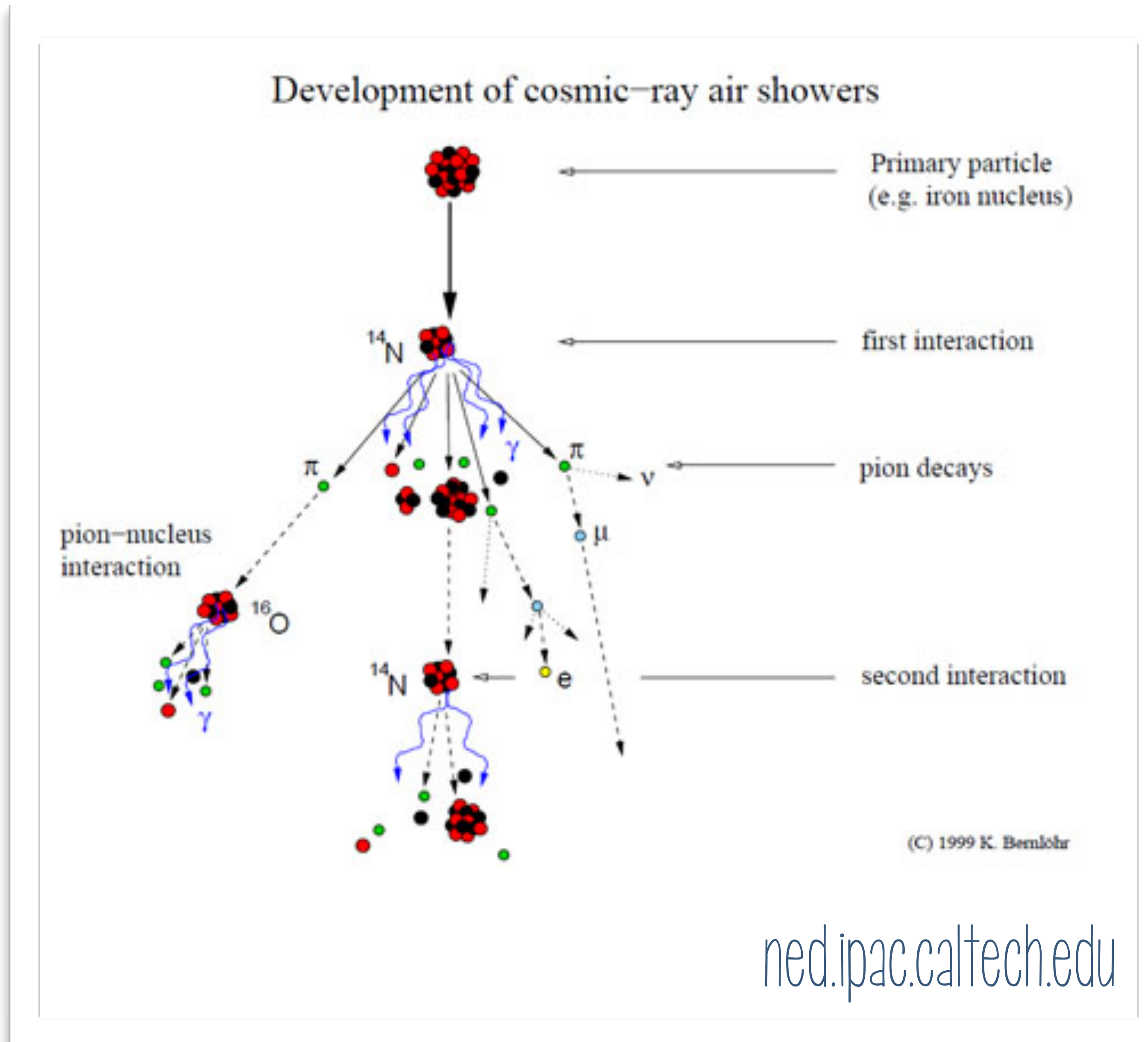
Extensive Air Showers (EAS)



When a high-energy PROTON enters the earth's atmosphere ...

- the secondary nucleons and charged pions continue to multiply until the energy per particle is no longer above the threshold for multiple pion production (~1GeV)
- eventually the cascade just consists of the electromagnetic component
- once shower maximum is reached, the e^+s and e^-s are rapidly attenuated due to ionisation
- the lateral spread of hadronic showers is usually much greater than that of gamma-ray showers
  - due to the large TRANSVERSE MOMENTUM given to pions in strong interactions
- these showers also have a longer penetrating tail, due to the large number of particles reaching ground level

important later



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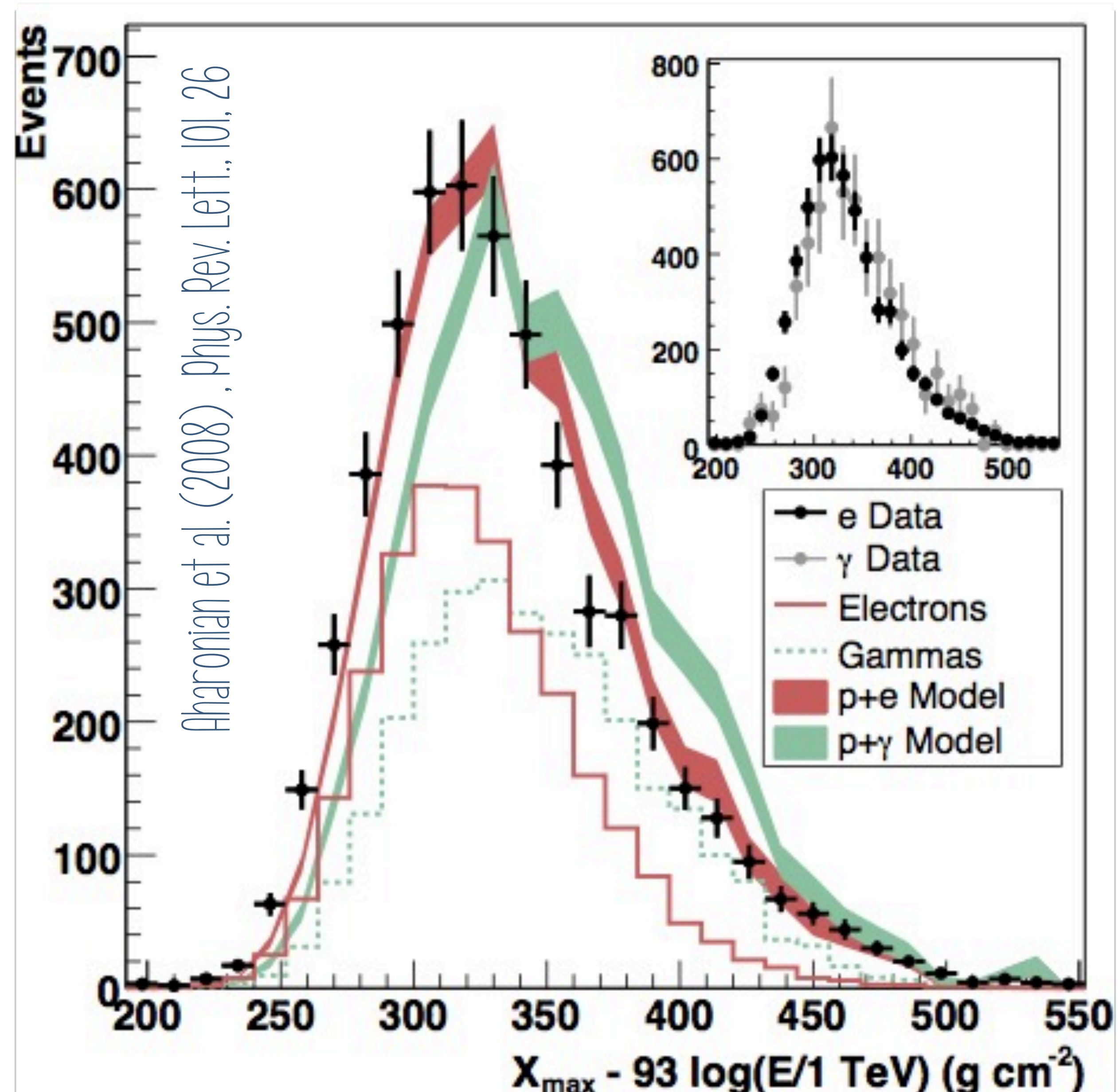
Extensive Air Showers (EAS)

When a high-energy ELECTRON* enters the earth's atmosphere ...

*electron = electron or positron

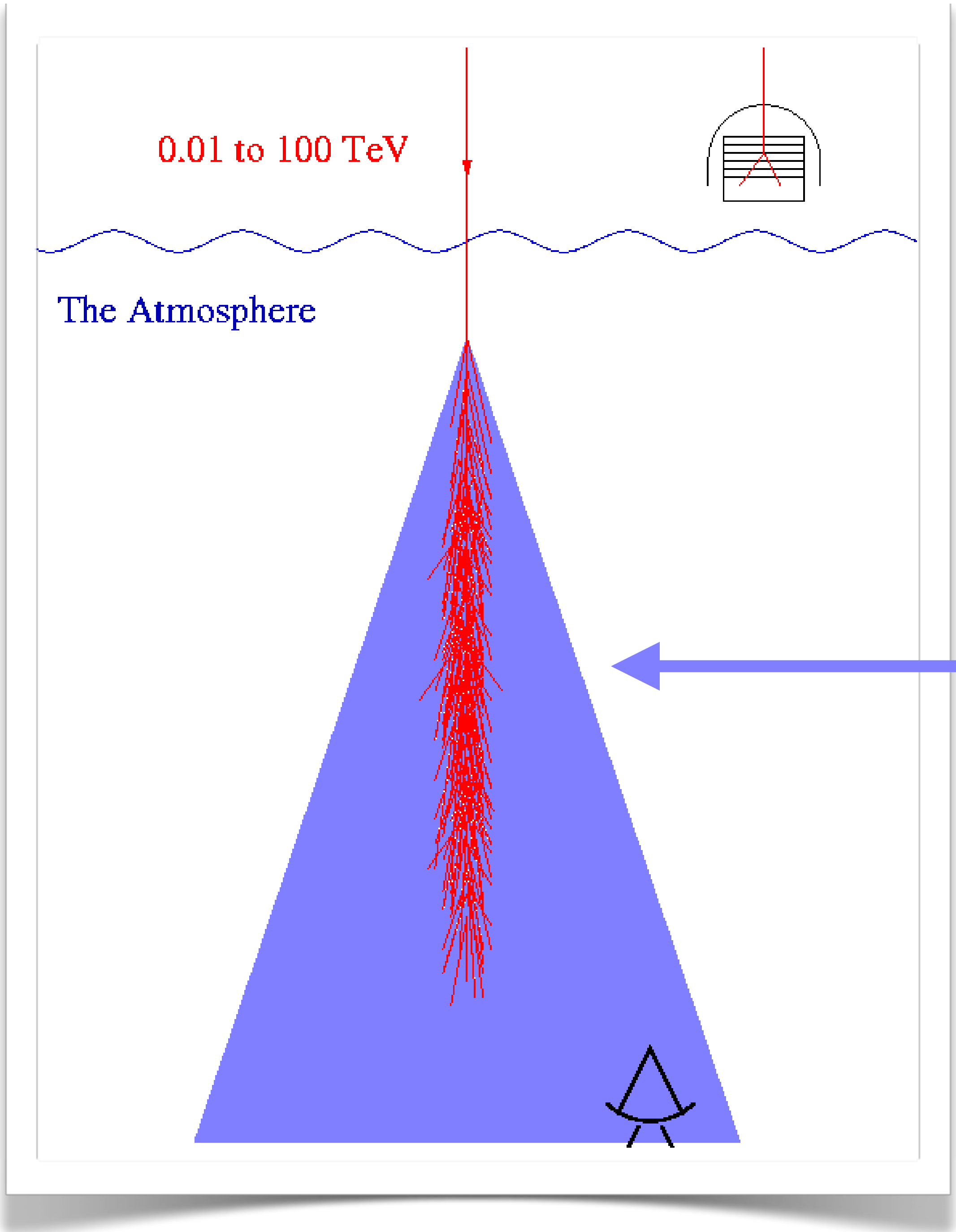
- **propagation of CR electrons* is severely limited by energy losses via synchrotron and inverse Compton scattering**
  - implication is that the sources of TeV electrons must be local (< 1 kpc)
- **CR e⁻s are less than 1% of the hadronic background**
- e⁻-initiated showers are extremely difficult to differentiate from gamma-ray showers
  - ➡ start to develop & produce light earlier than gamma-showers, but attenuate rapidly
- the only useful separation parameter is the depth of the shower maximum
  - ➡ it occurs at about 20 g cm^{-2} (37 g cm^{-2} for gammas)
  - ➡ half a radiation length higher in the atmosphere



Distribution of reconstructed shower maximum for HESS data compared to simulations

Cherenkov Radiation

When a high-energy particle or gamma ray enters the earth's atmosphere ...



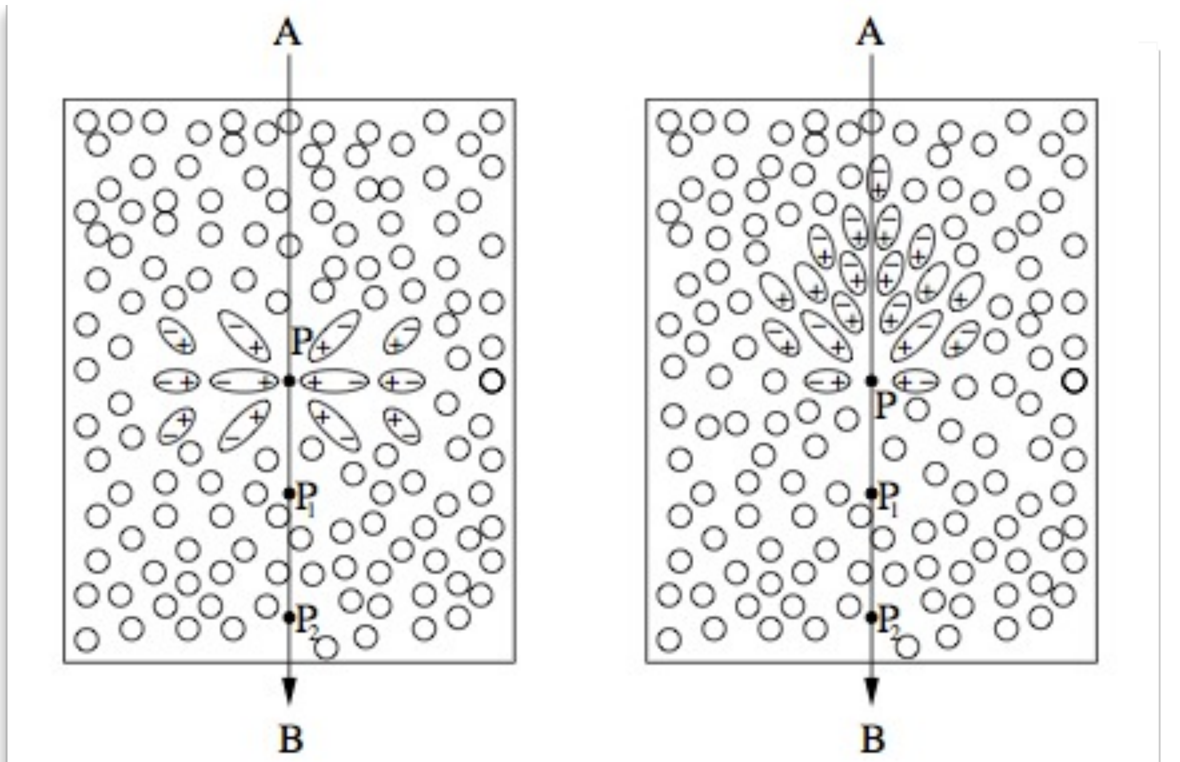
... the shower of charged particles is accompanyed by CHERENKOV RADIATION

Cherenkov Radiation
4/11

Cherenkov* Radiation

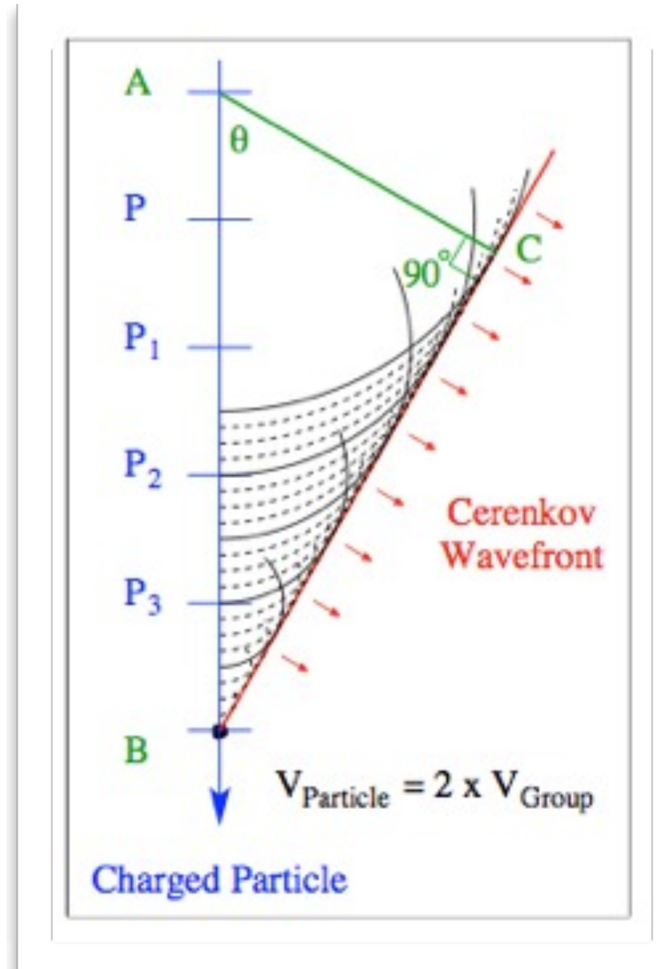
*Čerenkov

CHERENKOV RADIATION: when a charged particle travels through a medium with a velocity greater than the velocity of light in that medium



e- moves relatively slowly

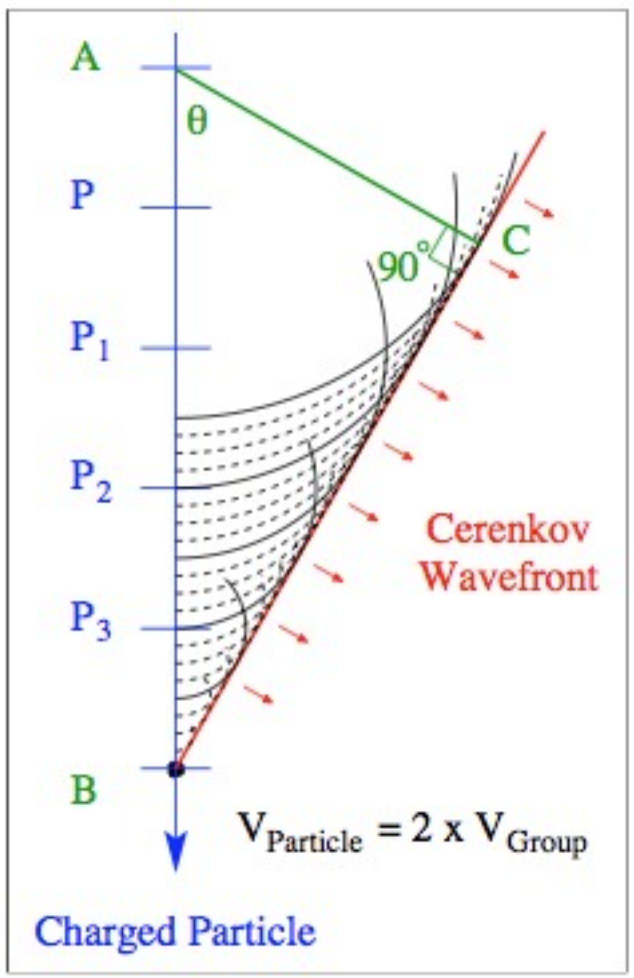
e- with velocity close to c



- When the charged particle (say, an e-), passes close to the atoms of a material, it distorts their alignment such that the positive charges of the nuclei are attracted towards it.
- When the e- has passed, the atoms relax back to their original shapes causing a brief electromagnetic pulse - polarisation moves on to be centred on P_1 etc...
- When the velocity of the e- is greater than the phase velocity of light in that medium, it is possible for the wavelets from all portions of the track to be in phase with one another, thus producing a coherent wave-front at a well defined angle to the path of the electron.
- This coherence occurs when the electron travels from A to B, in the same time as the radiation emitted by the atoms of the material, travels from A to C.

Cherenkov Radiation

CHERENKOV RADIATION: when a charged particle travels through a medium with a velocity greater than the velocity of light in that medium



e- has velocity βc & it travels from A to B in time Δt:

$$AB = \beta c \Delta t \quad \text{and} \quad AC = \frac{c}{n}\Delta t$$

since: $$\cos\theta = \frac{AC}{AB}$$

we can arrange the first two equations to get:

$$\cos\theta = \frac{1}{\beta n}$$

... the criterion for cherenkov radiation to be emitted

cherenkov angle is max for β=1. There is a min velocity for the charged particle & also a threshold energy

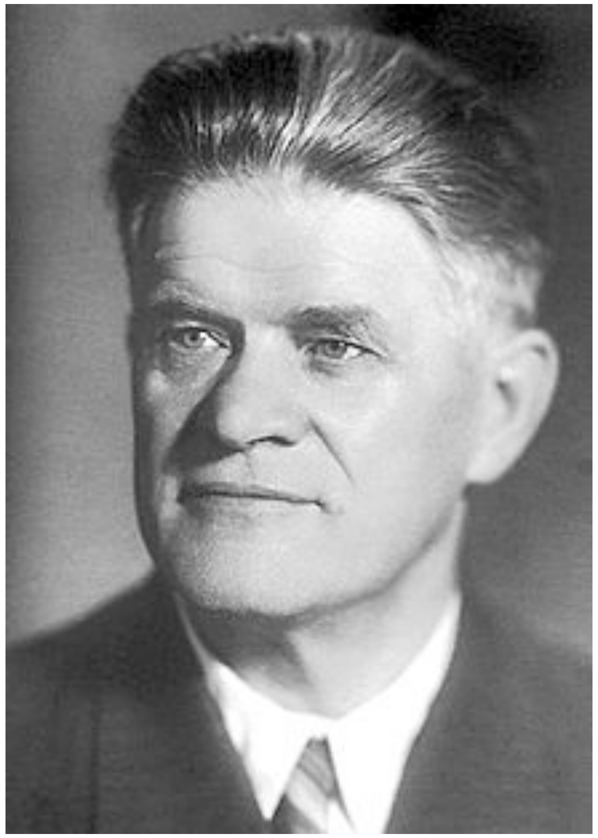
$$\theta_{max} = \cos^{-1}\frac{1}{n} \qquad \beta_{min} = \frac{1}{n} \qquad E_{min} = \frac{m_0 c^2}{\sqrt{1-\beta_{min}^2}}$$

The medium is the radiator - not the particles!

Cherenkov Radiation

CHERENKOV RADIATION:

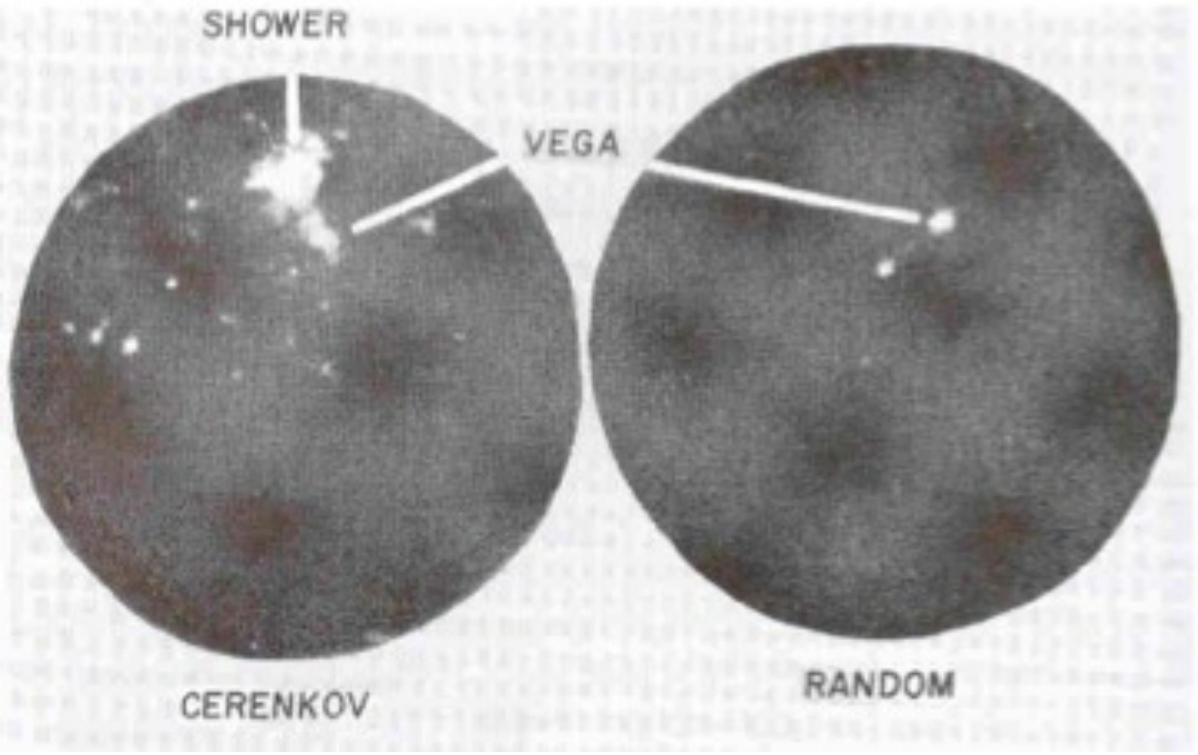
- It is named after the Russian scientist Pavel Alekseyevich Cherenkov. He shared the Nobel Prize in physics in 1958 with Ilya Frank and Igor Tamm for its discovery - made in 1934. He was the first to detect it experimentally.
- **Cherenkov radiation is blue - UV light**
- In 1948, it was suggested by Blackett that there should be a small contribution (10^{-4} of total starlight) to the light of night sky from Cherenkov radiation
- very briefly, it outshines the night sky - need very fast electronics to record it above this background



P. A. Cherenkov (1904 - 1990)

VHE Technique

image intensifier pictures of night sky
with and without Cherenkov shower



Work by David Hill (M.I.T.) and Neil Porter (U.C.D.) in 1960

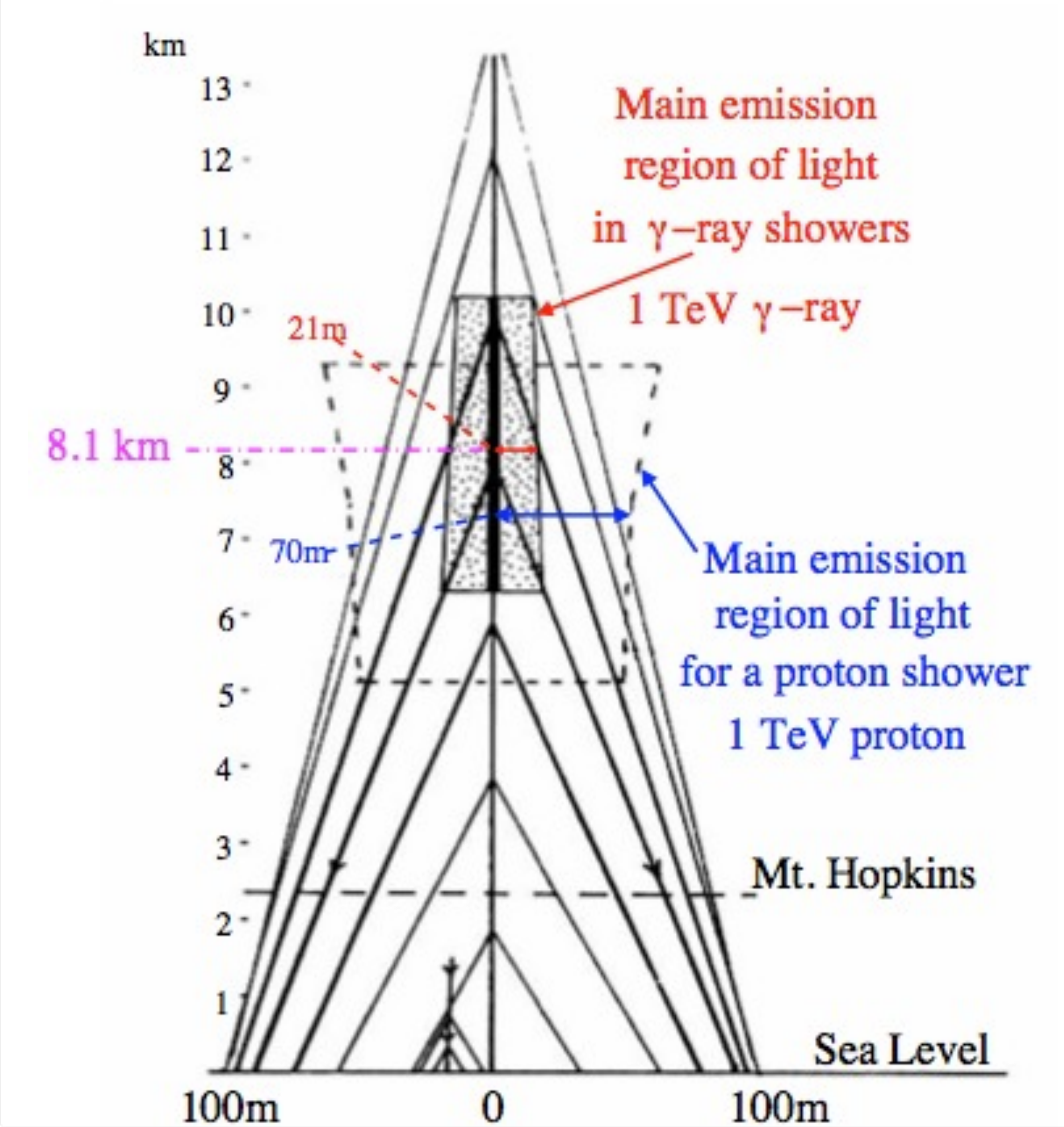
on short timescales, the light from the Cherenkov shower outshines Vega!*

* The FIFTH brighest star in the sky

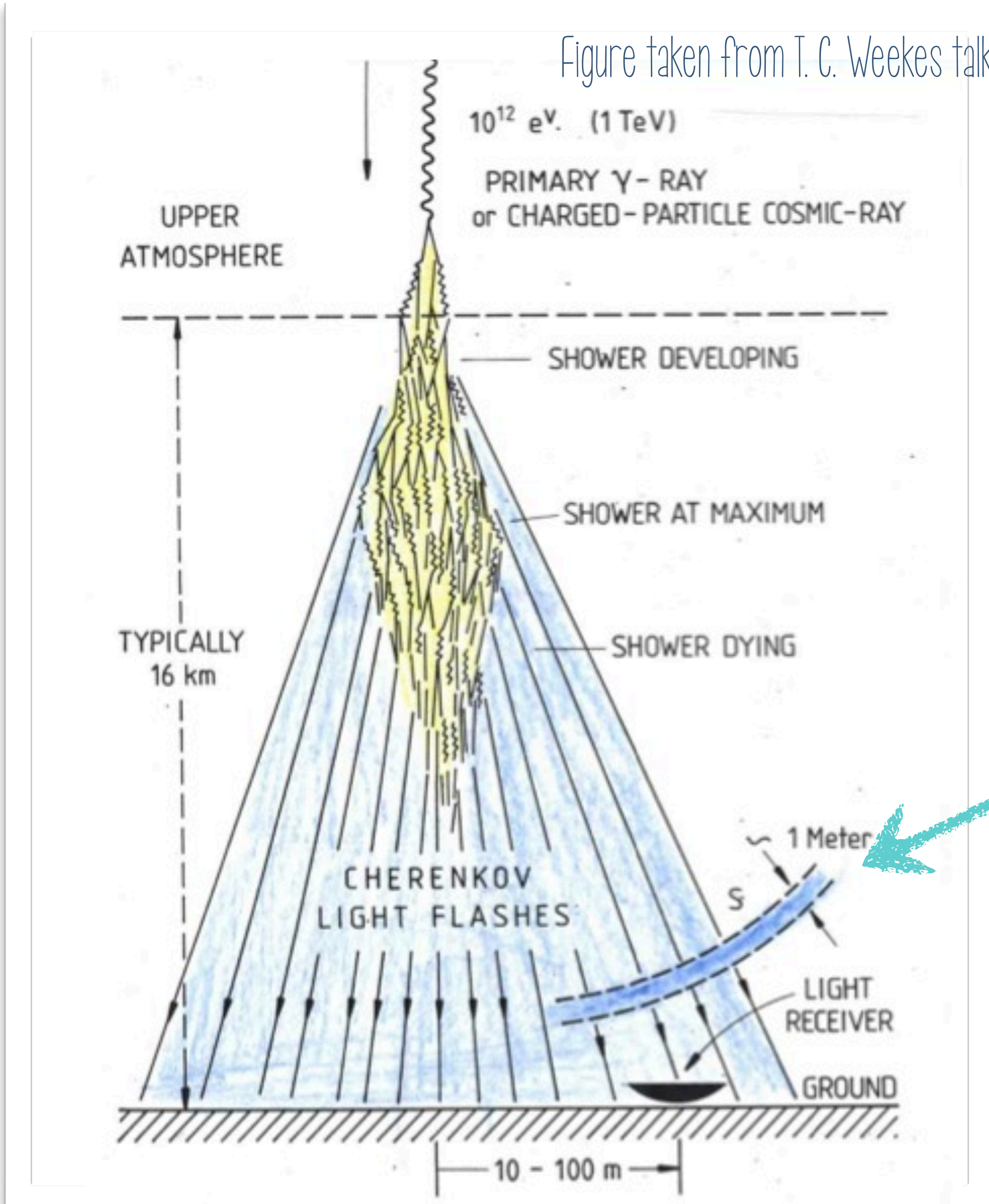
Cherenkov Radiation

- the stippled box contains the main emission of Cherenkov light in a 1 TeV gamma-ray shower
- **the median altitude is 8.1 km**
- at these heights, half the emission occurs at radial distances within the box
- the dashed-box indicates the main emission region for Cherenkov light in a proton shower of the same energy

Figure adapted from Hillas (1996), Space Science Reviews, 75, 17



Cherenkov Radiation



for a 100 GeV primary, we get about 5 photons m^{-2} out to about 120m from the axis

at detector level, the shower results in a pool of light of:

~120m diameter

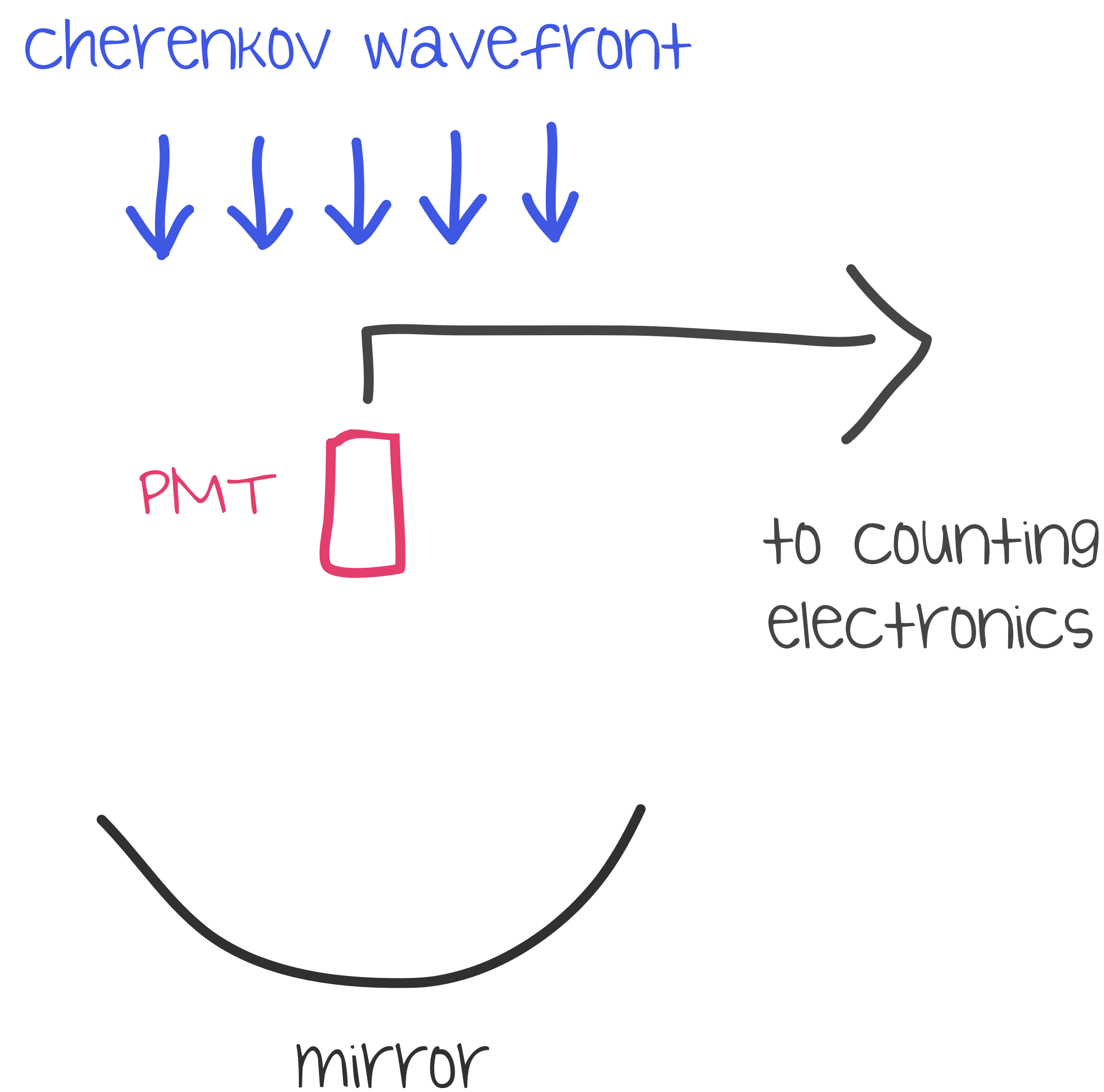
~1m (2-3 ns) thickness

First Generation VHE Telescopes
5/11

First Generation VHE Telescopes

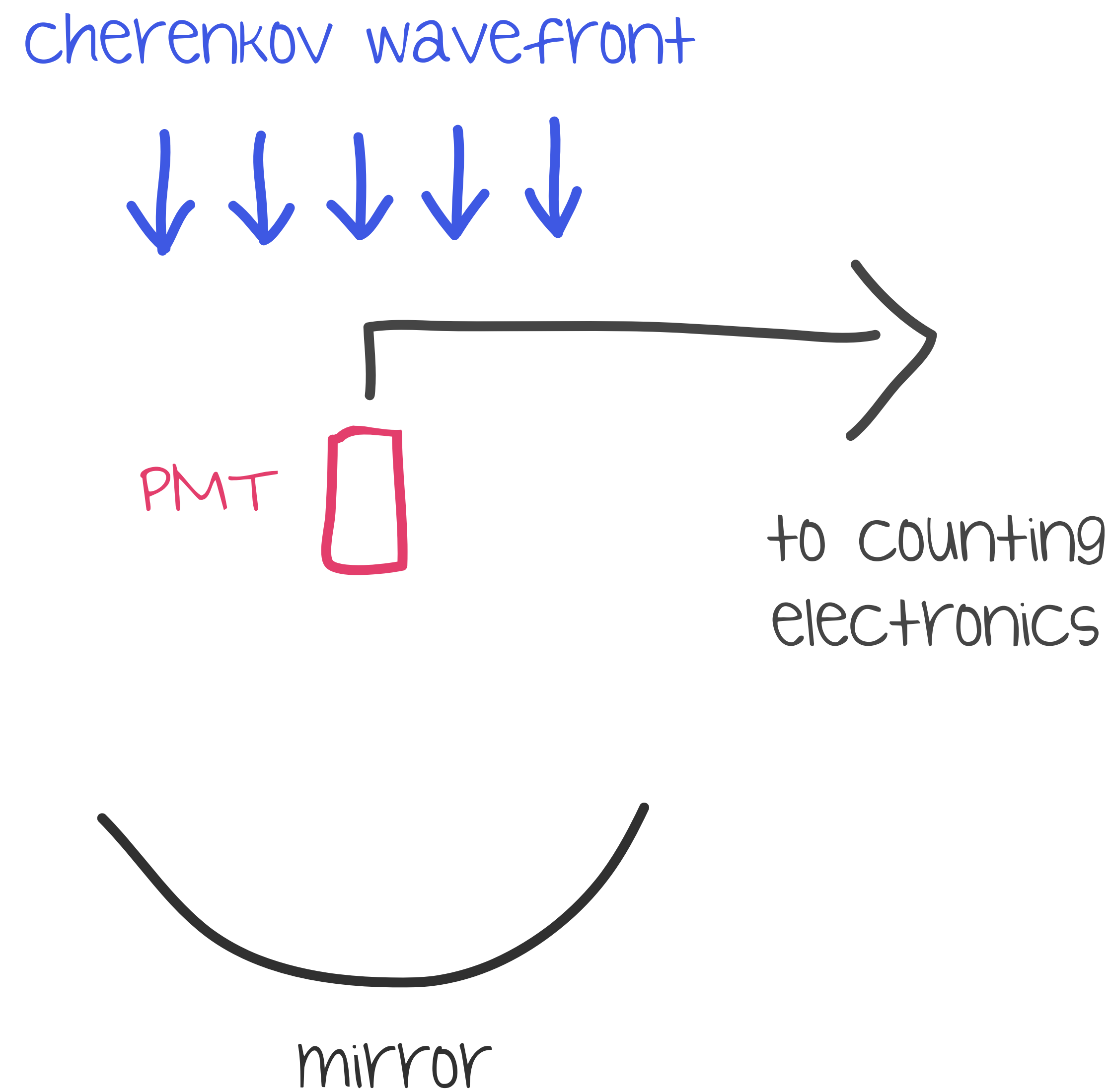
To DETECT & record the Cherenkov light from an air shower, we need:

- a mirror to gather & focus the light
- a FAST detector
- a means to trigger/record the image



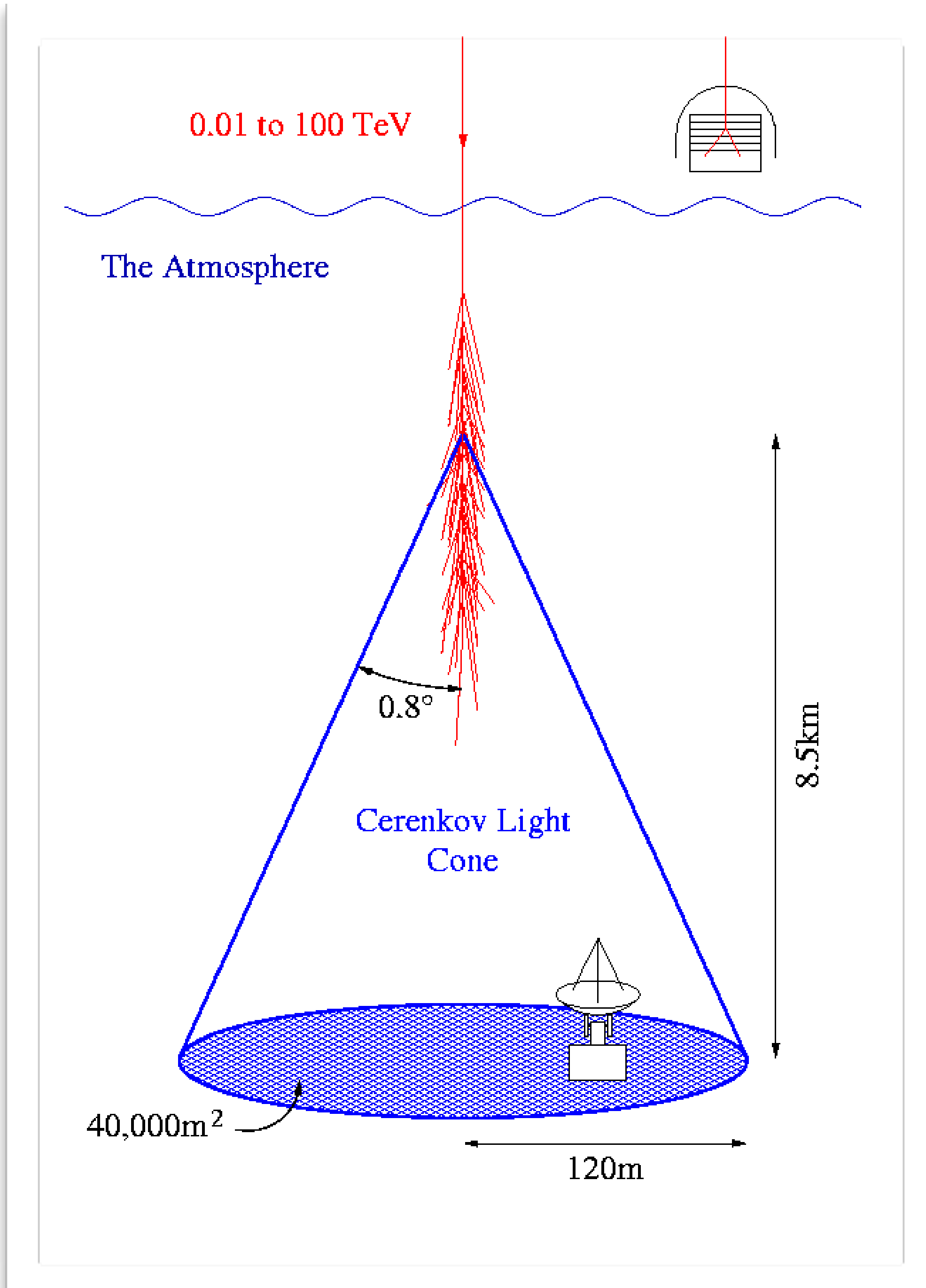
First Generation VHE Telescopes

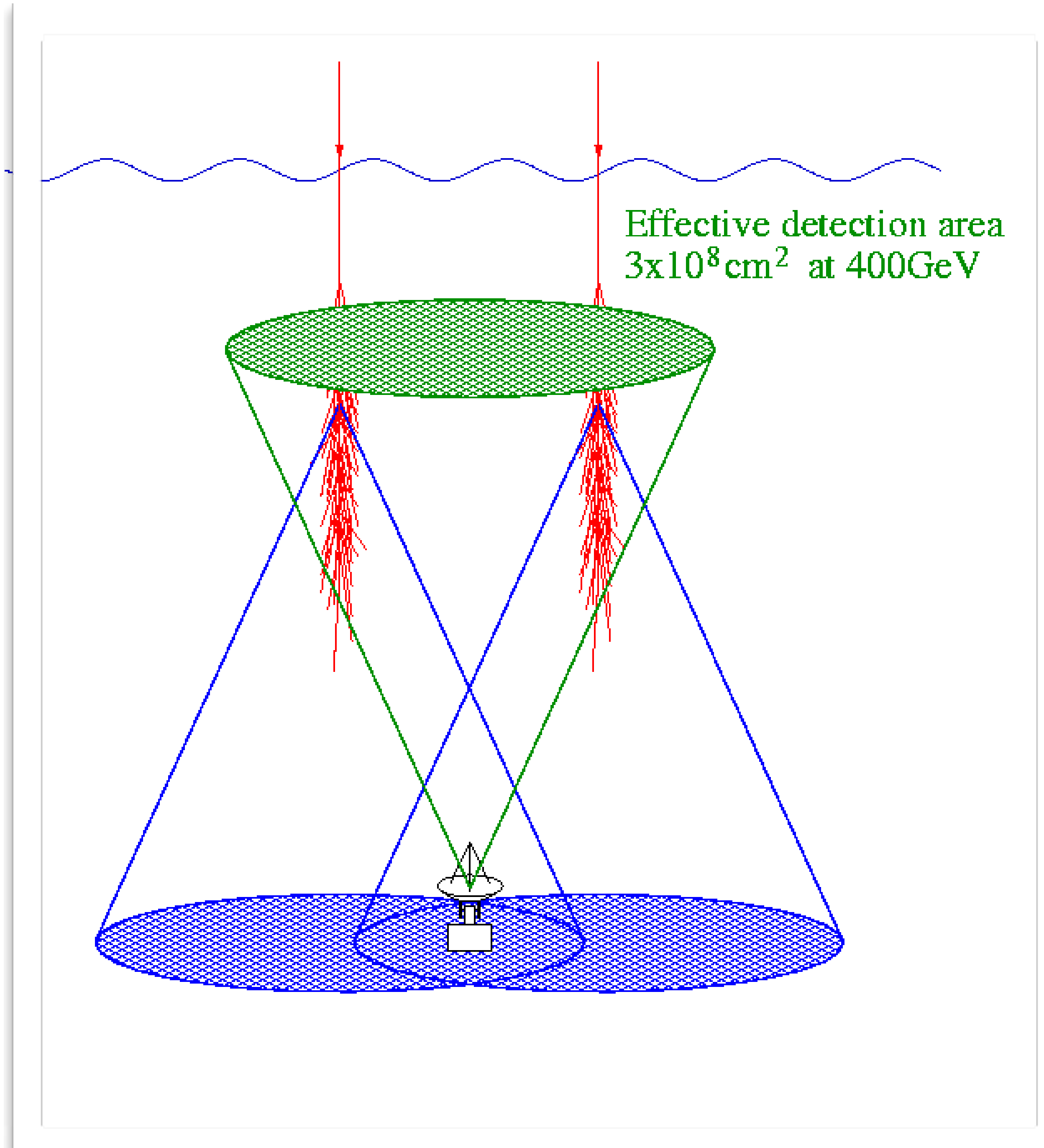
Galbraith and Jelley (1953), Harwell - U.K.



First Generation VHE Telescopes

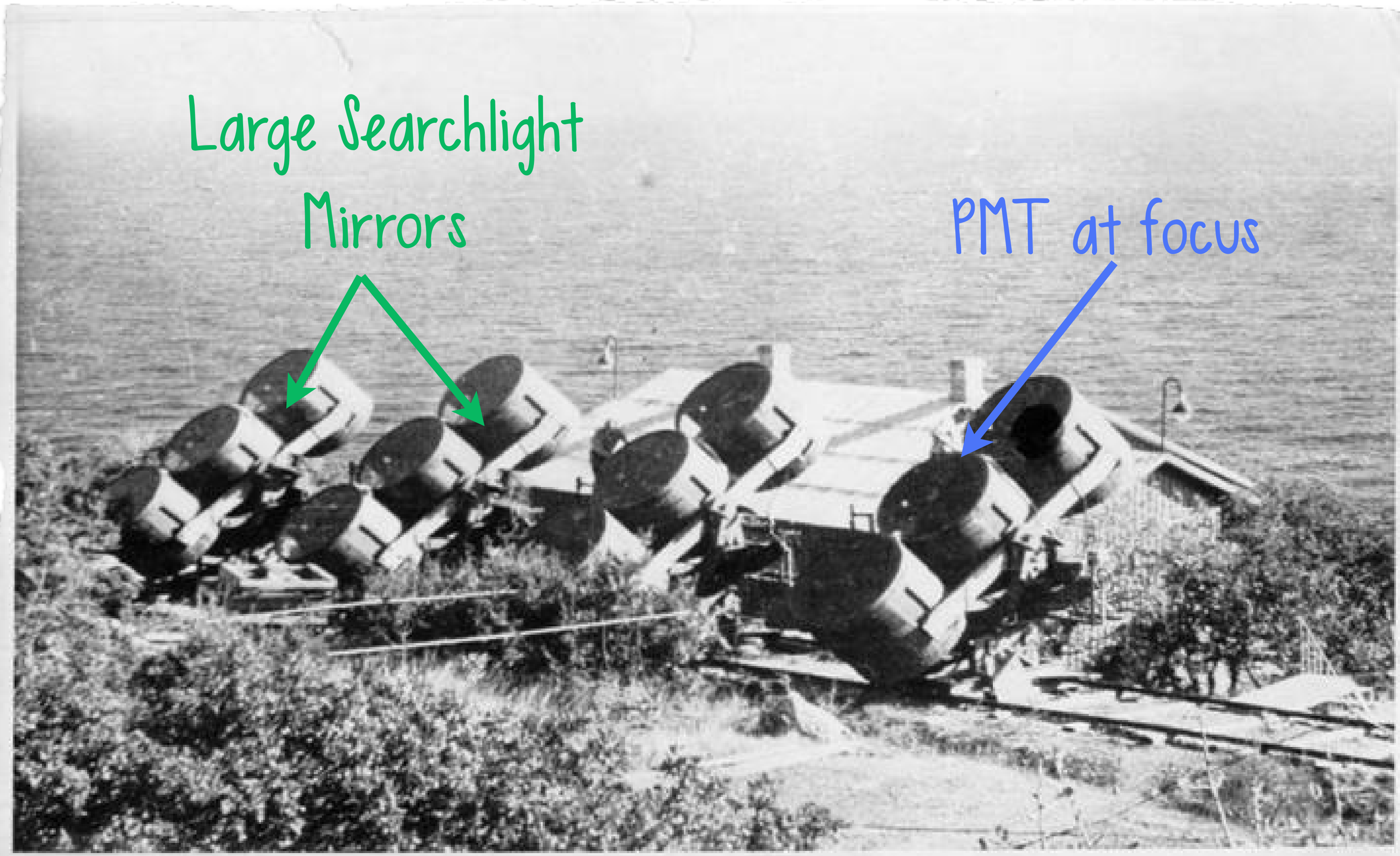
Large Collection Area ~ $10^4 m^2$





First Generation VHE Telescopes

The Early Days



Crimea Experiment 1960 - 1965

First Generation VHE Telescopes

The Early Days

Glencullen, Ireland
1962-66 (ish)

University College Dublin group*
- led by Neil Porter in collaboration with J. V. Jelley

WWII surplus gun mount and search-light mirrors

TARGETS: quasars, variable stars, supernova remnants, Crab

but...

*Still very active in VHE gamma-ray astronomy

T. C. Weekes (2012 Fermi Summer School)

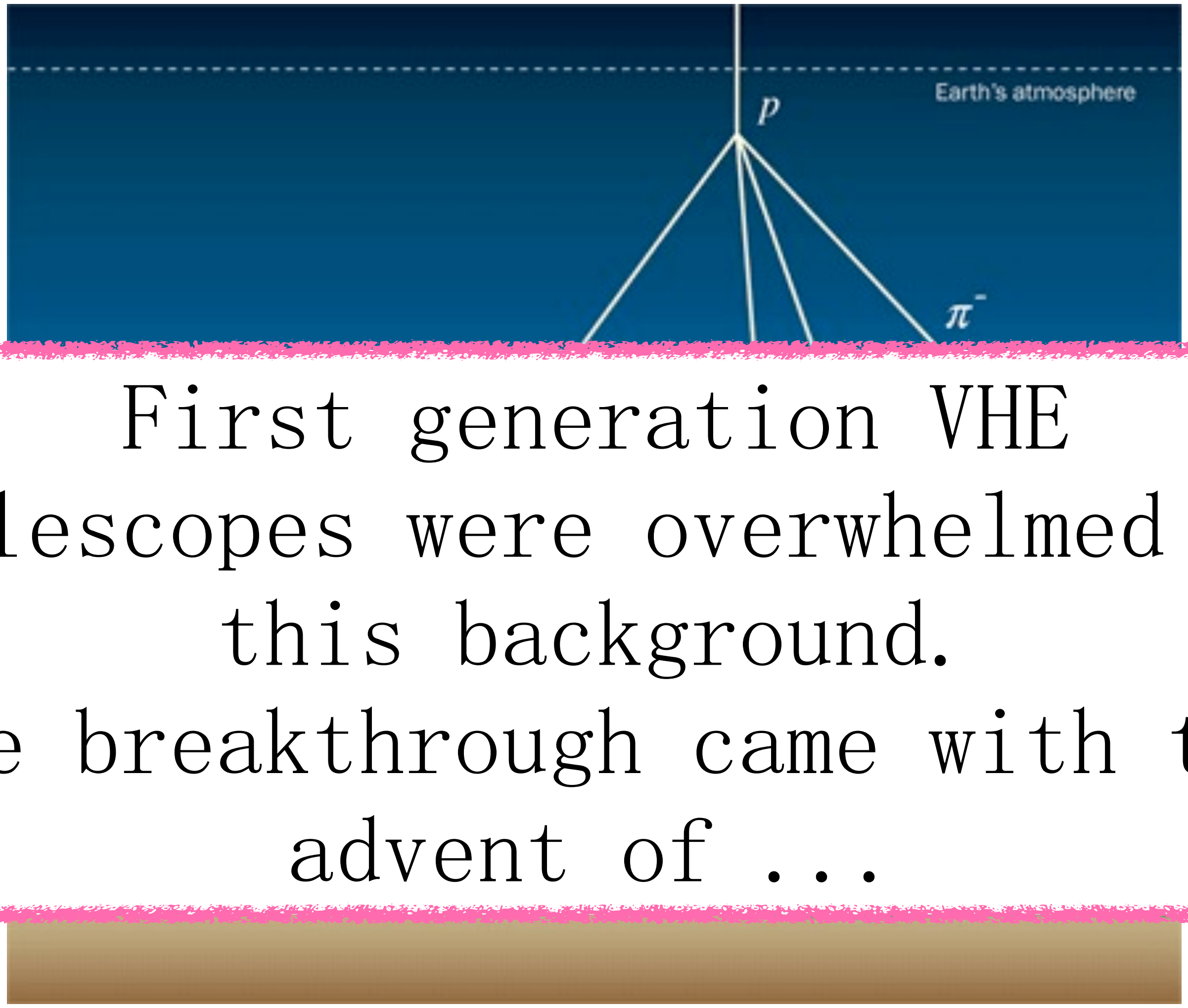
First Generation VHE Telescopes

The Early Days

Glencullen, Ireland
1962-66 (ish)

but this actually wasn't the real limitation ... these telescopes did successfully detect Cherenkov radiation from air showers

First Generation VHE Telescopes



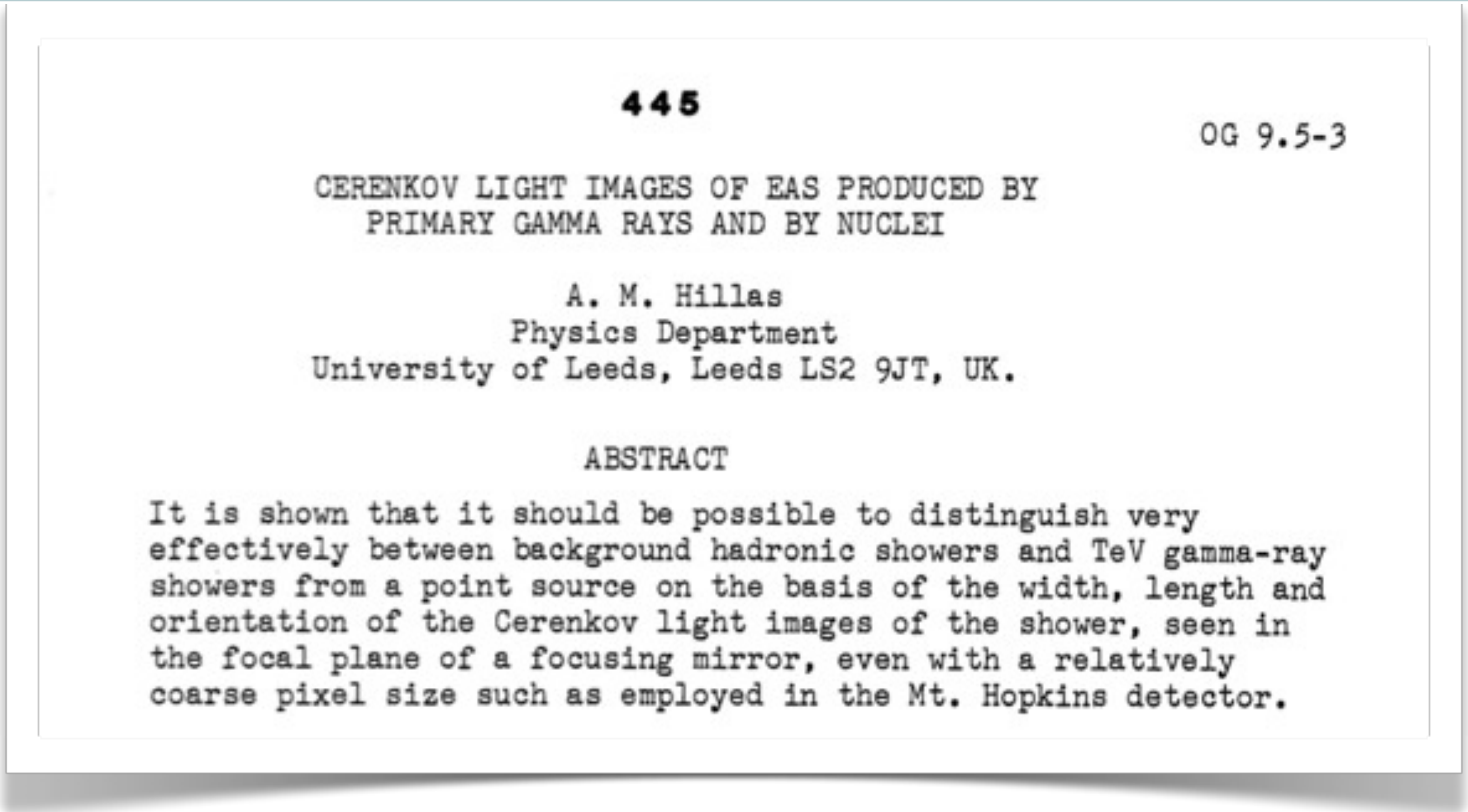
First generation VHE telescopes were overwhelmed by this background.
The breakthrough came with the advent of ...

The problem is that > 99% of the events that trigger the camera are induced by cosmic rays

We need to extract the gamma-ray signal from this overwhelming background

The Imaging Atmospheric Cherenkov Technique 6/11

The Imaging Atmospheric Cherenkov Technique



445

OG 9.5-3

CERENKOV LIGHT IMAGES OF EAS PRODUCED BY PRIMARY GAMMA RAYS AND BY NUCLEI

A. M. Hillas
Physics Department
University of Leeds, Leeds LS2 9JT, UK.

ABSTRACT

It is shown that it should be possible to distinguish very effectively between background hadronic showers and TeV gamma-ray showers from a point source on the basis of the width, length and orientation of the Cerenkov light images of the shower, seen in the focal plane of a focusing mirror, even with a relatively coarse pixel size such as employed in the Mt. Hopkins detector.

"Cerenkov light images of EAS produced by primary gamma", Proc. 19th ICRC (La Jolla), Vol. 3, 445 (1985)

- A.M. HILLAS

The Imaging Atmospheric Cherenkov Technique

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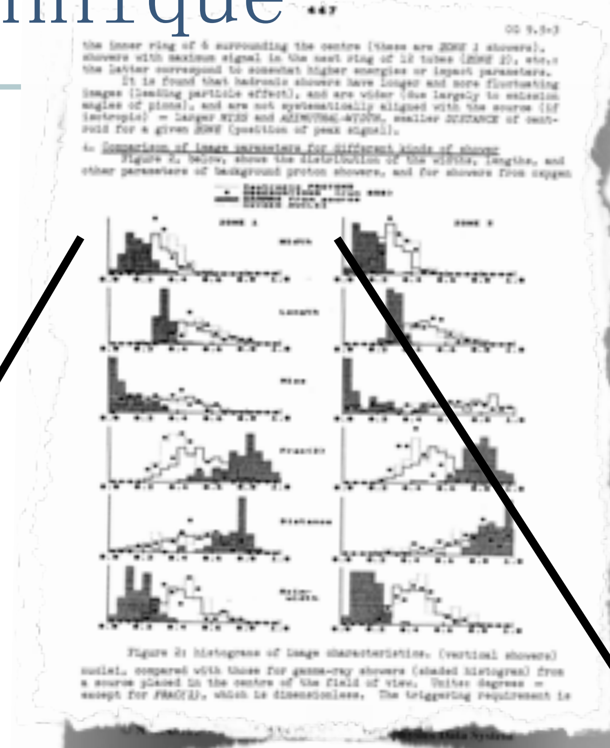
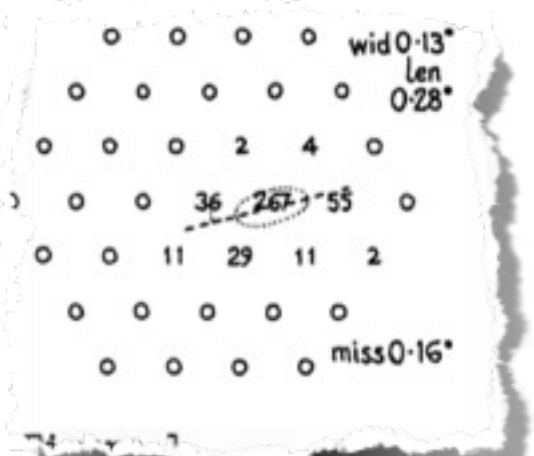
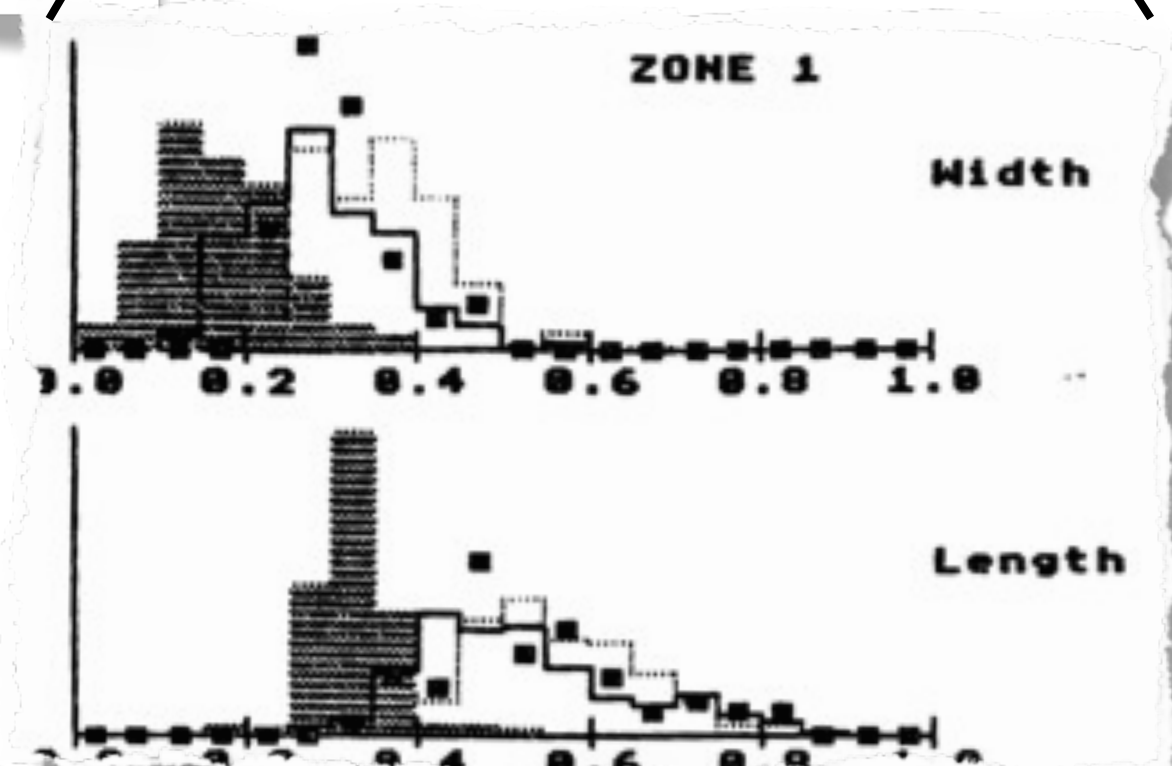




distribution for gamma rays is shaded



"Cerenkov light images of EAS produced by primary gamma", Proc. 19th ICRC (La Jolla), Vol. 3, 445 (1985)

remember from earlier...

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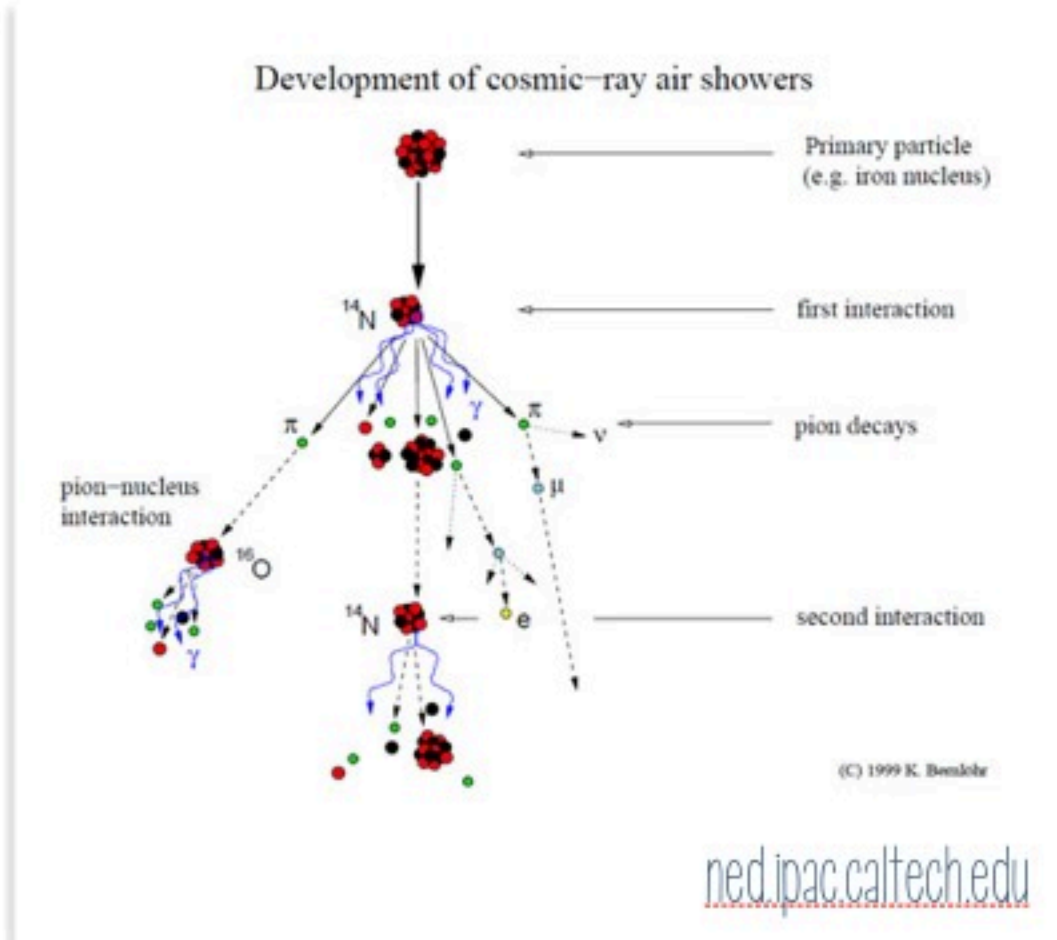
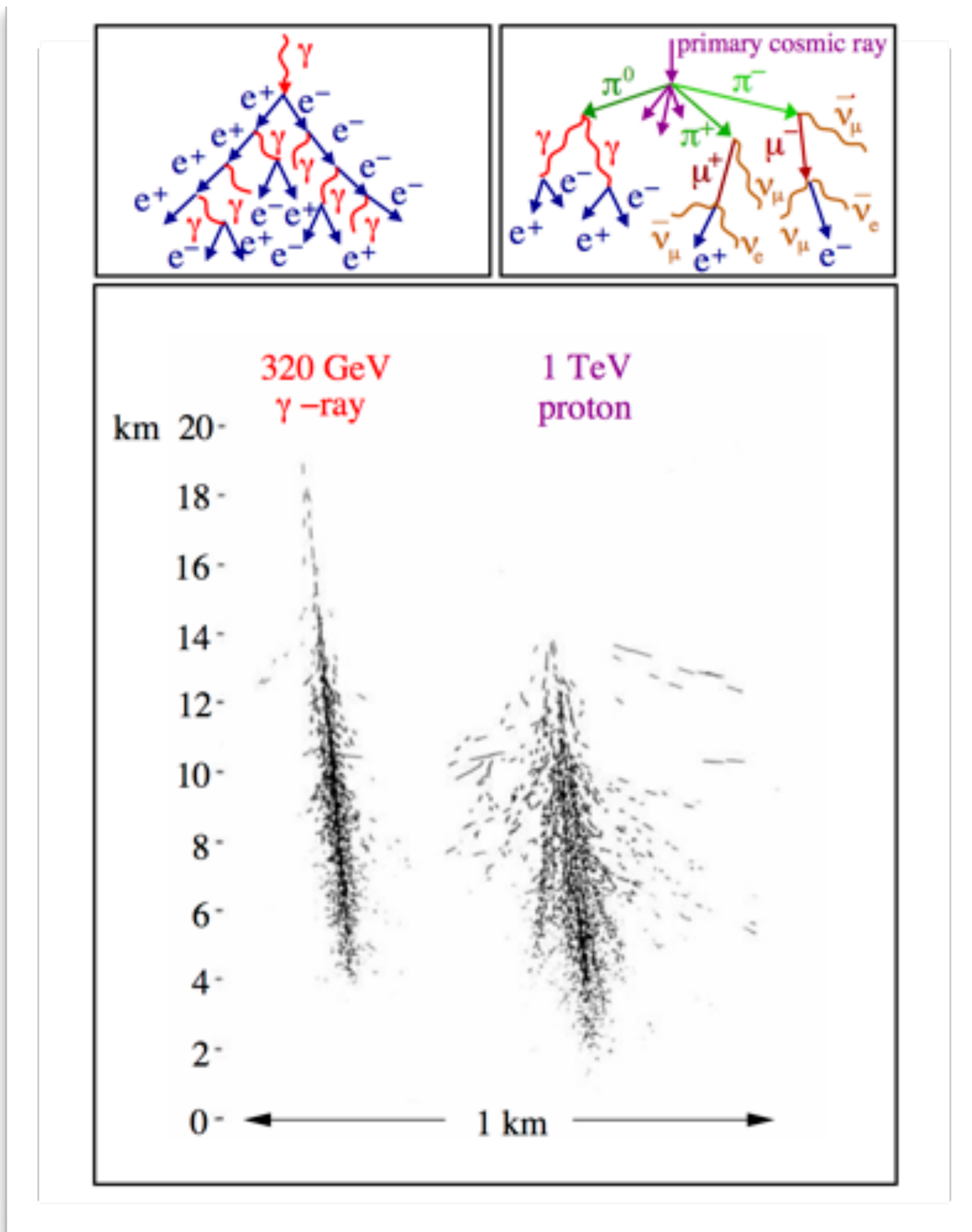
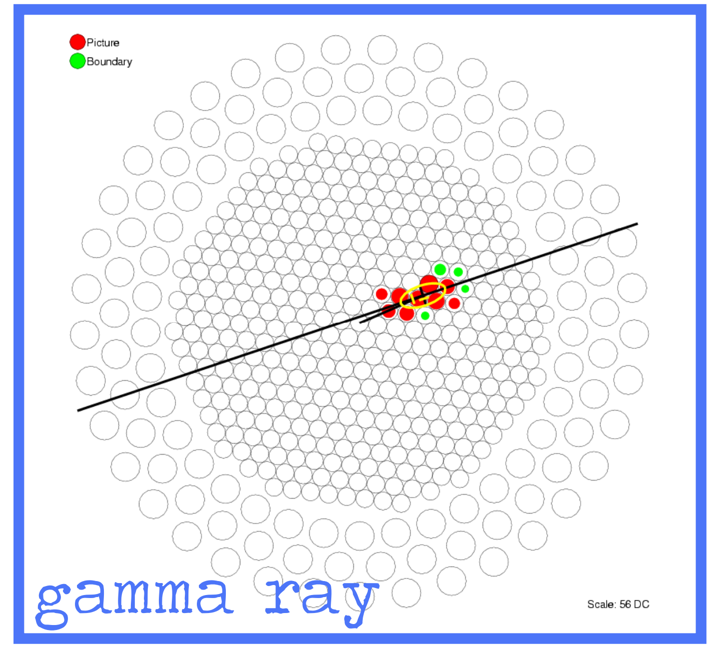


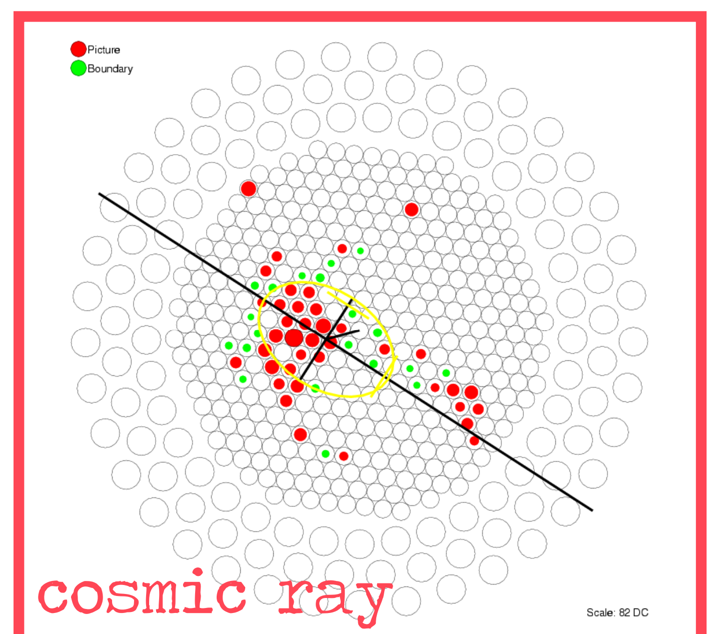
important later

The Imaging Atmospheric Cherenkov Technique

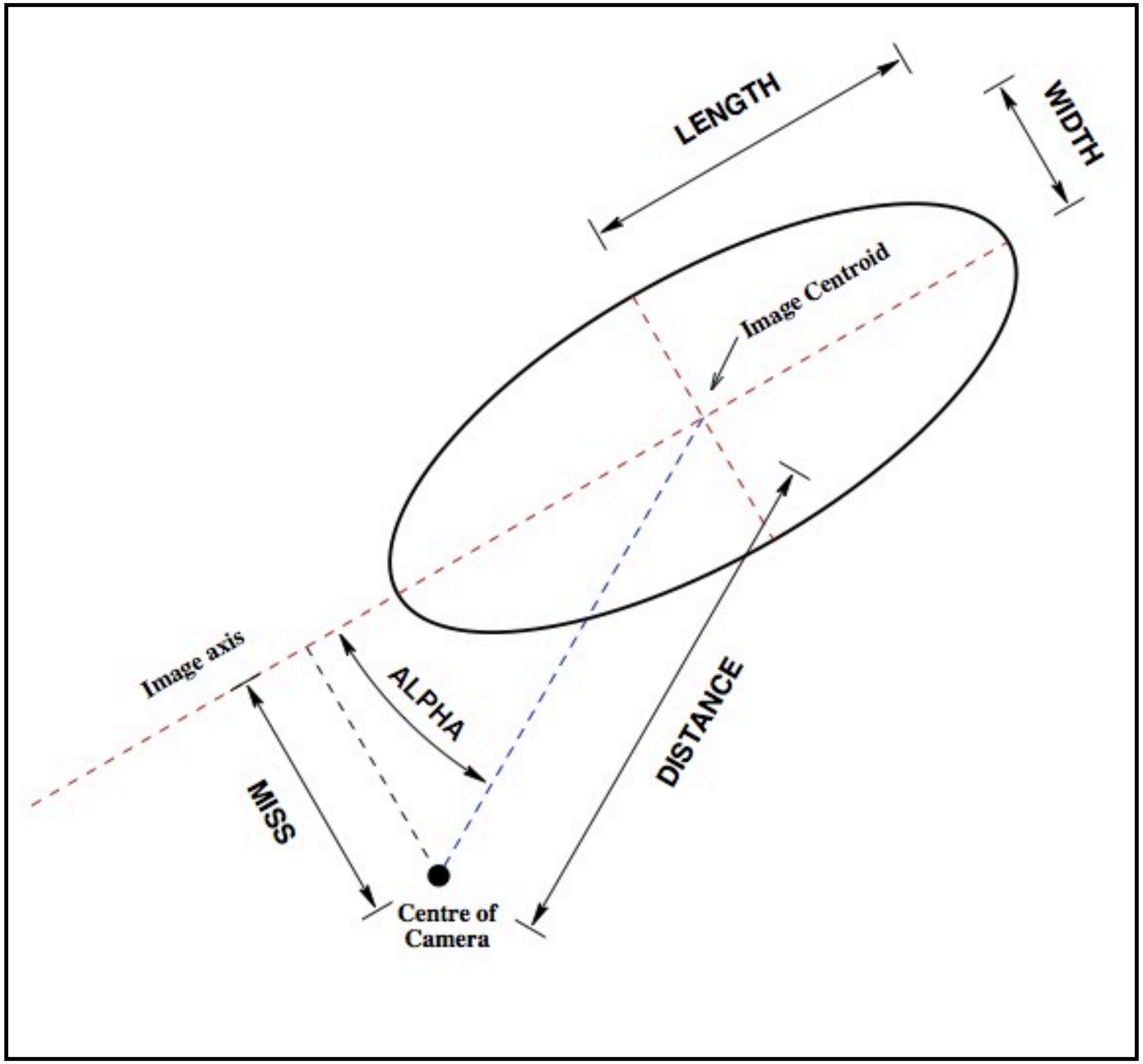
the different physical mechanisms that take place in gamma-ray & cosmic-ray induced showers affect the characteristics of their Cherenkov images

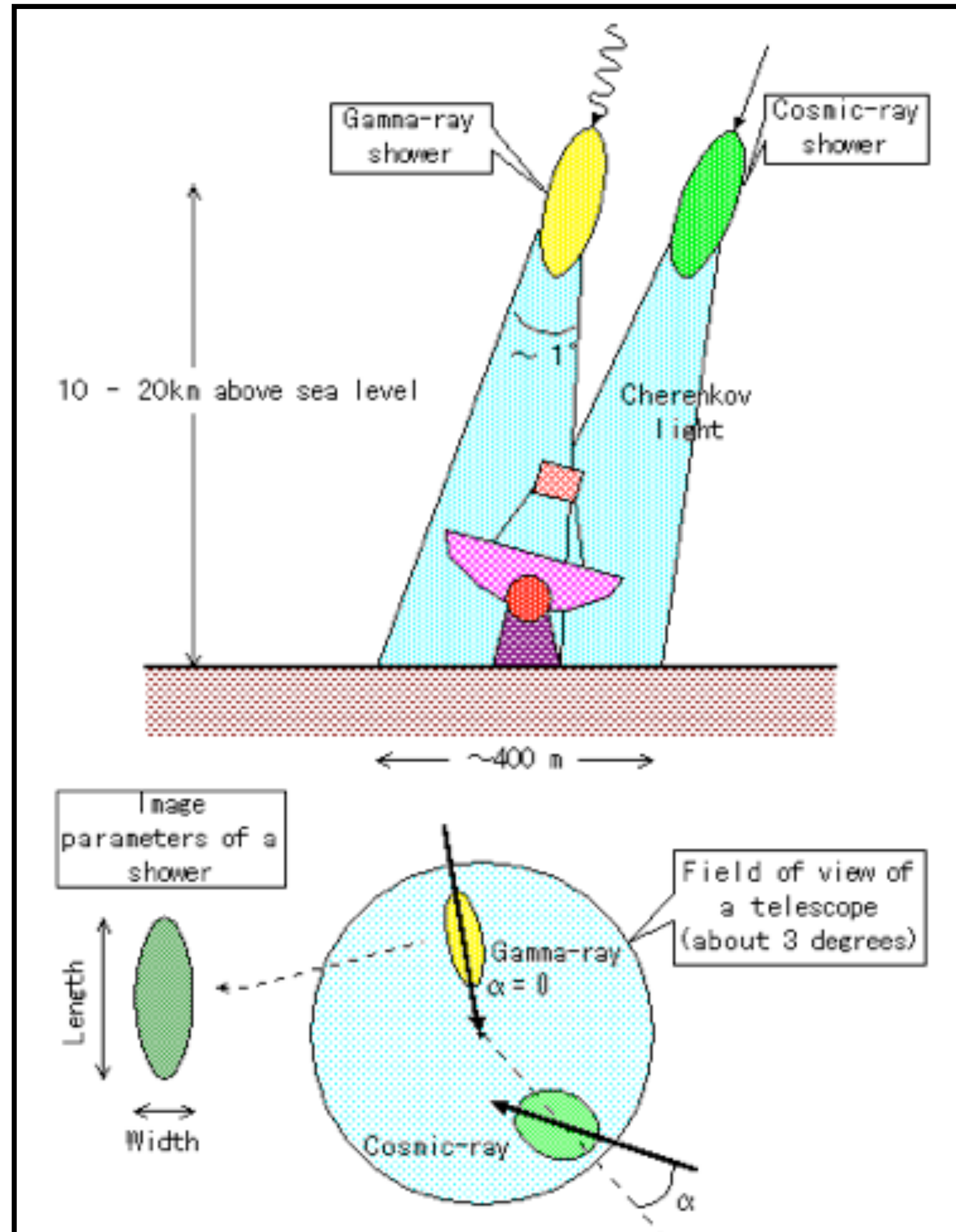






The Imaging Atmospheric Cherenkov Technique



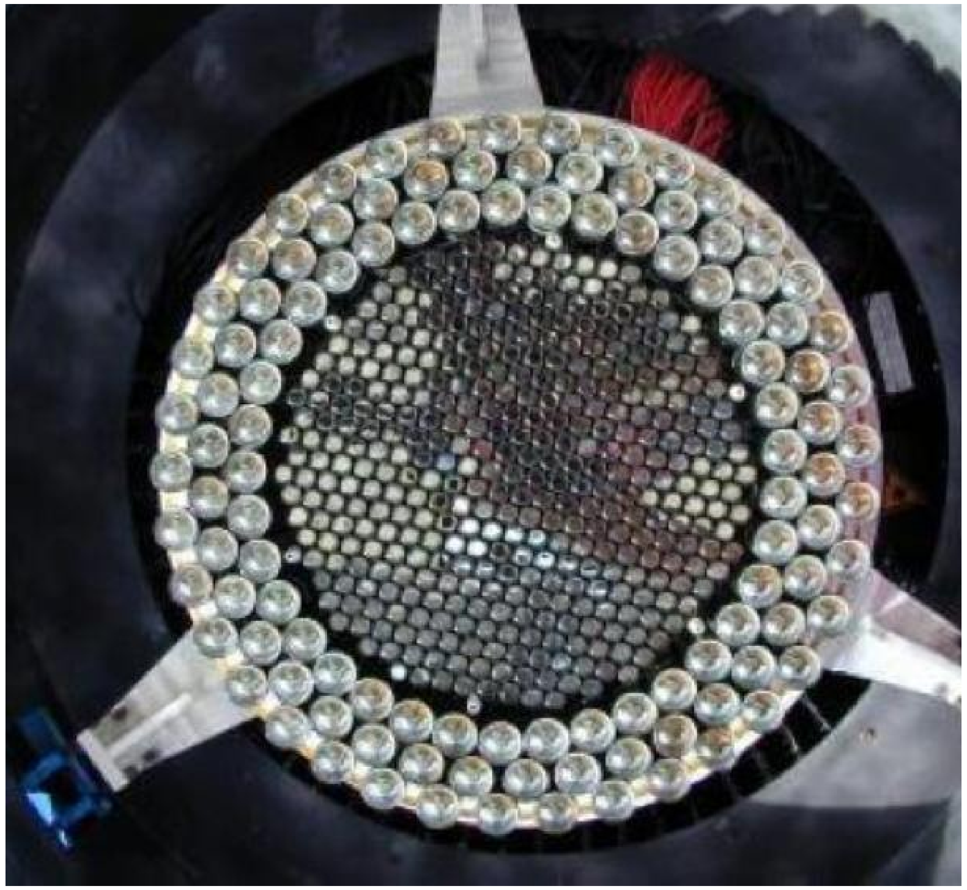


icrhp9.icrr.u-tokyo.ac.jp/method.html

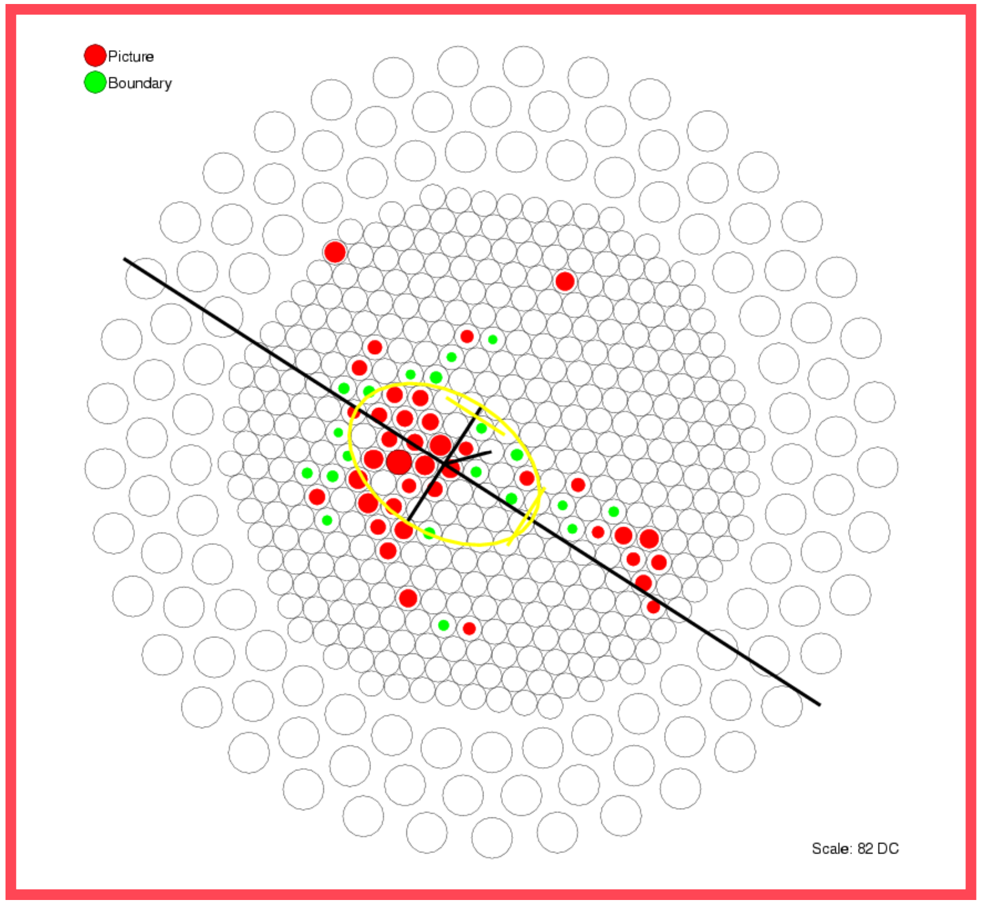
"Hillas parameters" (length, width, distance, alpha...) after A. M. Hillas

"Cerenkov light images of EAS produced by primary gamma", Proc. 19th ICRC (La Jolla), Vol. 3, 445 (1985)

The Imaging Atmospheric Cherenkov Technique

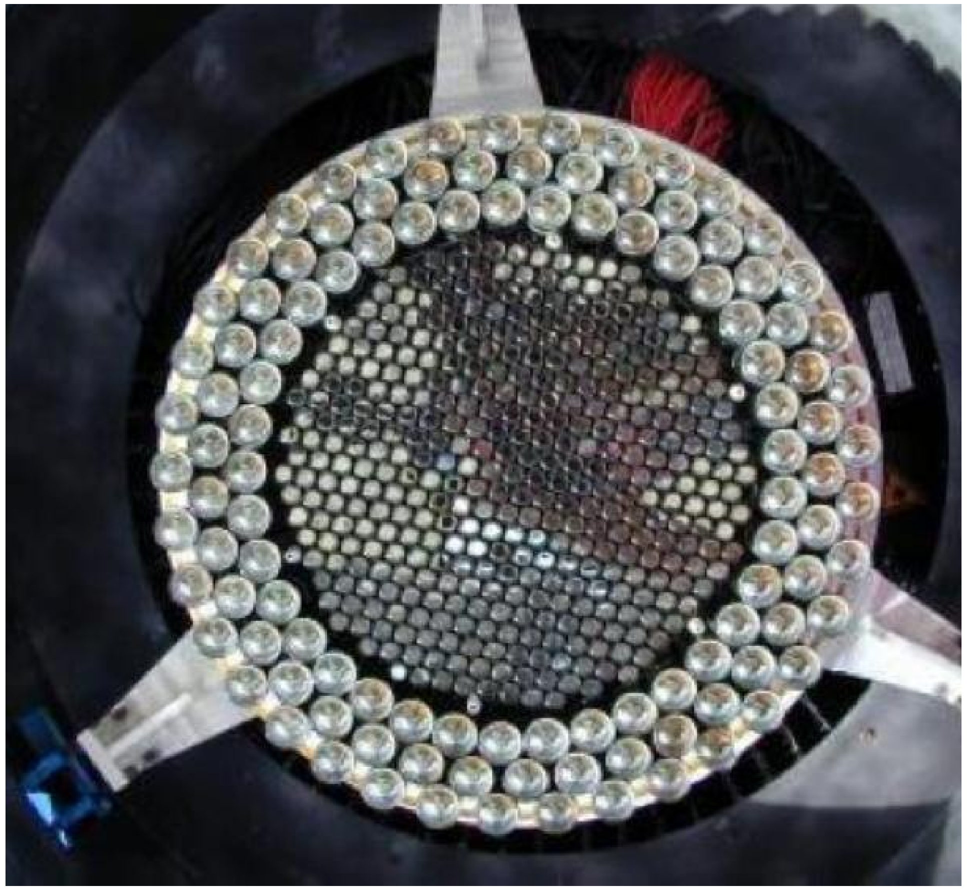


camera

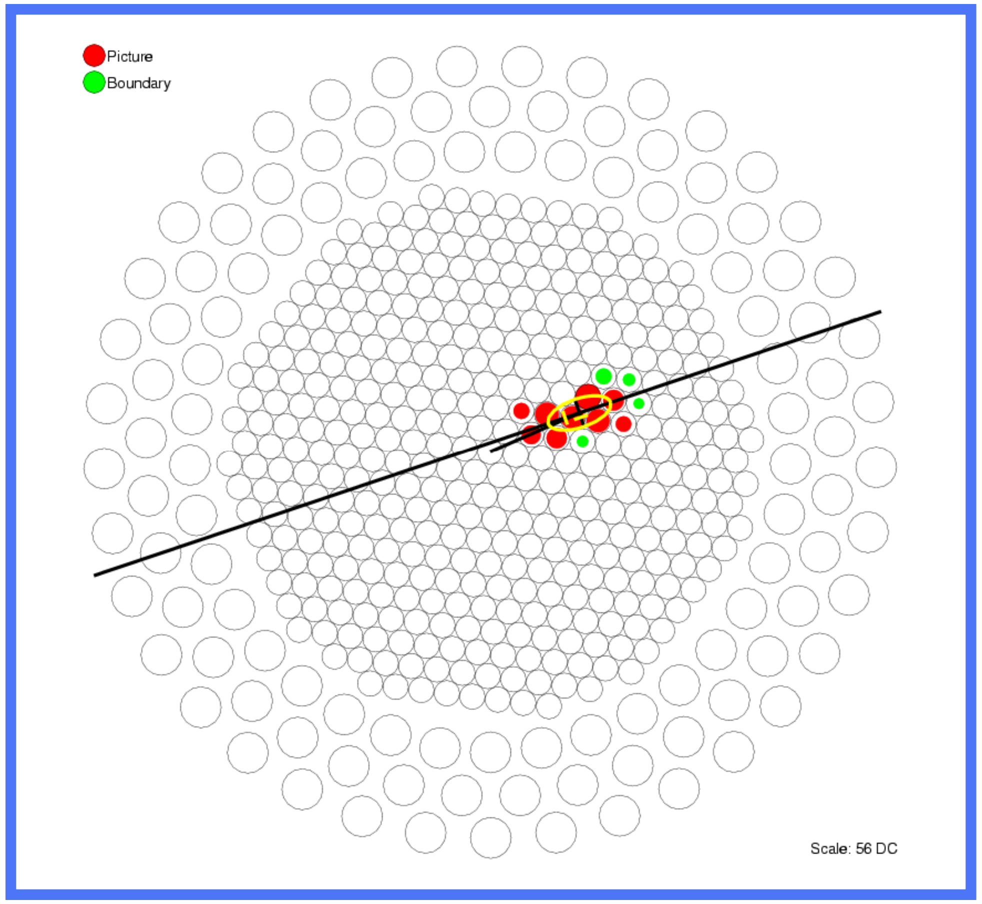


cosmic ray

The Imaging Atmospheric Cherenkov Technique



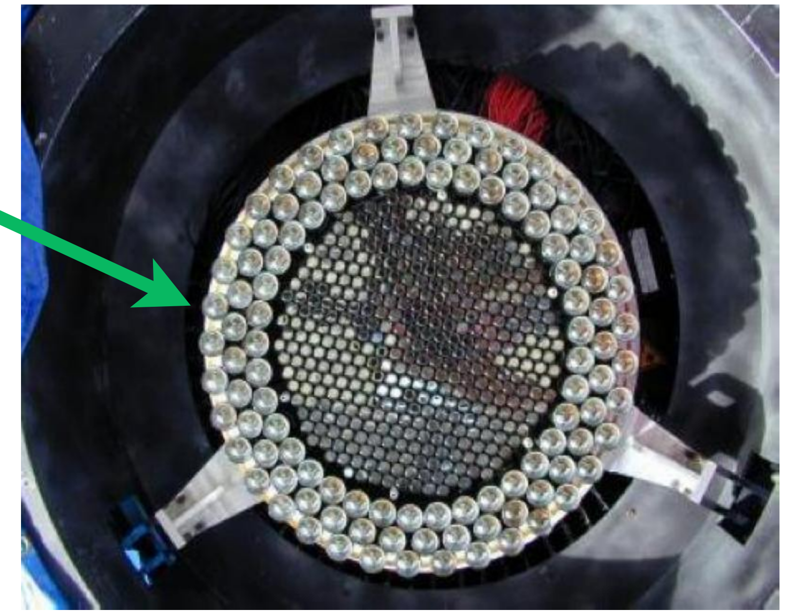
camera



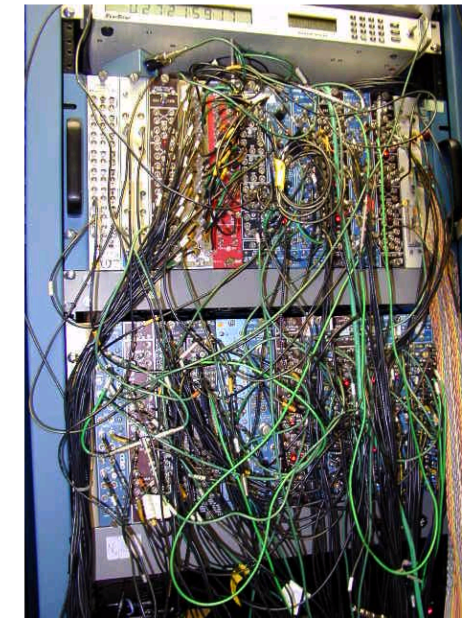
gamma ray

The Imaging Atmospheric Cherenkov Technique

The Whipple 10m Telescope



Pixelated Camera



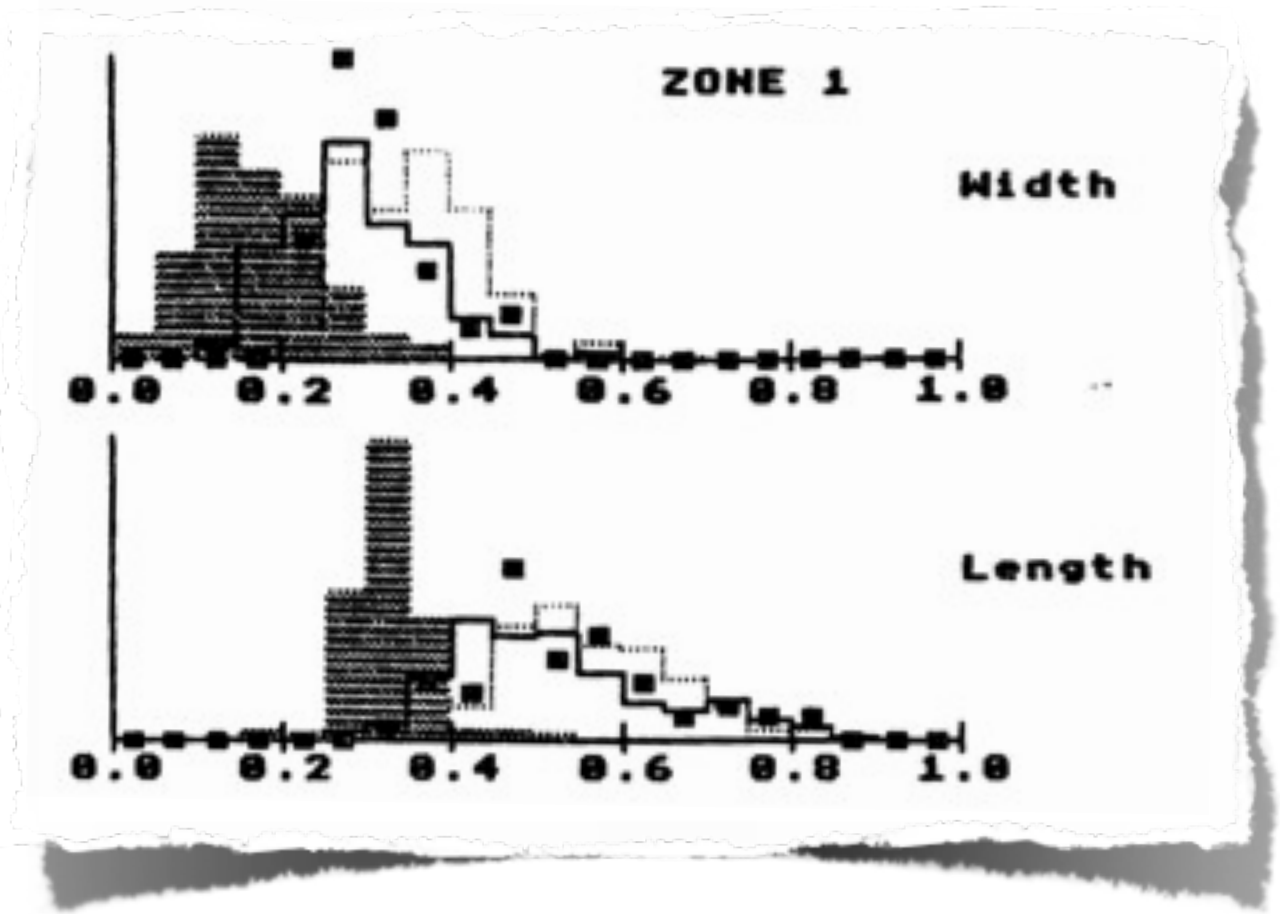
\+ ns electronics

= CHERENKOV IMAGES

The imaging technique was pioneered at the Whipple Telescope in Arizona

The Imaging Atmospheric Cherenkov Technique

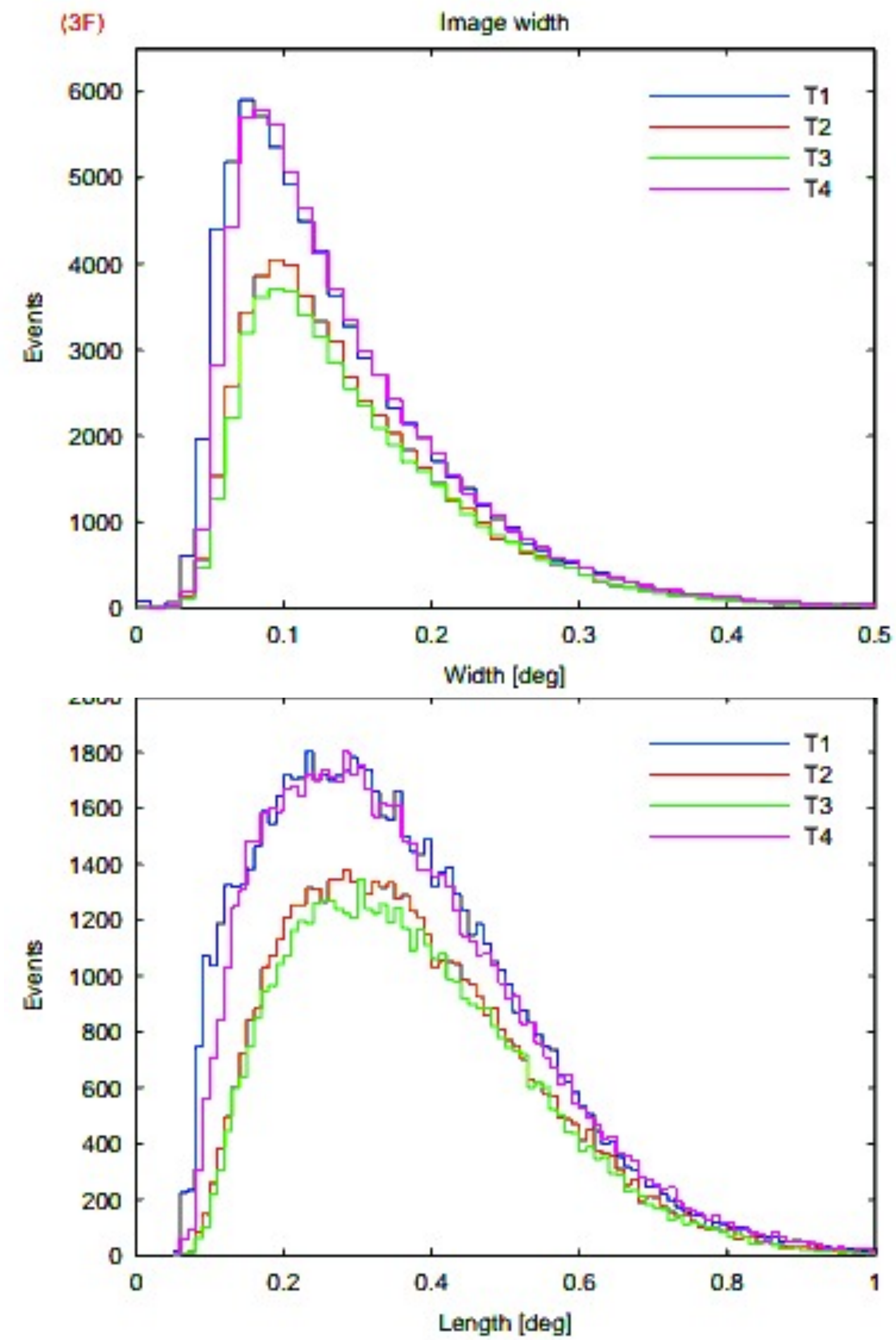
Original Hillas paper - simulated parameter distributions (1985)



shaded regions are gamma rays

"Cerenkov light images of EAS produced by primary gamma", Proc. 19th ICRC (La Jolla), Vol. 3, 445 (1985)

Actual parameter distributions from VERITAS (~2008)



The Imaging Atmospheric Cherenkov Technique

The Astrophysical Journal, Vol. 342, 379 (1989)

With the advent of imaging came the first ever TeV gamma-ray source, **the Crab Nebula**, thus establishing the field of

TEV GAMMA-RAY ASTRONOMY

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKES,[1] M. F. CAWLEY,[2] D. J. FEGAN,[3] K. G. GIBBS,[1] A. M. HILLAS,[4] P. W. KWOK,[1] R. C. LAMB,[5] D. A. LEWIS,[5] D. MACOMB,[5] N. A. PORTER,[3] P. T. REYNOLDS,[1,3] AND G. VACANTI[5]

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Received 1988 August 1; accepted 1988 December 9

ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^{2} s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

I. INTRODUCTION

The observation of polarization in the radio, optical, and X-ray emission from the Crab Nebula is usually taken as confirmation of the synchrotron origin of the radiation and is a strong indication of the presence in the nebula of a reservoir of relativistic electrons with energies up to 1 TeV. The presence of the radio pulsar, PSR 0531, near the center of the nebula provides a source for the on-going injection of relativistic electrons into this reservoir. The collision of the synchrotron-radiating electrons with synchrotron-radiated photons within the nebula inevitably results in a hard photon spectrum (at some level) that extends from the X-ray into the gamma-ray energy range; the shape of the spectrum mirrors that of the soft photon spectrum but with greatly reduced intensity. The Compton synchrotron model of the nebula was first developed by Gould (1965) and was refined by Rieke and Weekes (1969) and by Grindlay and Hoffmann (1971). A strong flux of gamma rays was predicted with maximum luminosity in the 0.1–1.0 TeV energy range. The gamma-ray flux level depends on the strength of the nebular magnetic field, which is a free parameter in the model and is little constrained by observations at other wavelengths. However, based on equipartition arguments, it is estimated to be $\sim 10^{-3}$ G.

The observation of a flux of 0.14 TeV gamma rays from the Crab Nebula was reported by the Smithsonian group using the atmospheric Cerenkov technique (Fazio *et al.* 1972); based on observations that spanned 3 years, this detection was still only at the 3 σ level. This demonstrates both the weakness of the source and the lack of sensitivity of the technique. The detection of TeV gamma rays from the Crab Nebula is a confirmation of the Compton synchrotron model and gives a direct measure of the magnetic field. This measurement, which was conservatively interpreted as an upper limit, implies an average magnetic field of 3×10^{-4} G, or a radially symmetric ($1/r$) field with $B_0 = 1 \times 10^{-3}$ G at a distance of 0.1 pc from the pulsar (Grindlay 1976).

Subsequent to the discovery of PSR 0531 in the nebula, TeV gamma-ray observations concentrated on the pulsar because greater sensitivity could be achieved by the assumption of synchronization of the gamma-ray emission with the periodic radio emission. Several detections were reported at very high energies (Grindlay 1972; Jennings *et al.* 1974; Grindlay, Helmken, and Weekes 1976; Porter *et al.* 1976; Erickson, Fickle, and Lamb 1976; Vishwanath 1982; Vishwanath *et al.* 1985; Gupta *et al.* 1977; Gibson *et al.* 1982*b*; Dowthwaite *et al.* 1984; Turner *et al.* 1985; Bhat *et al.* 1986), but the statistical significance was not high, and upper limits were also presented which appeared to be in conflict with the reported fluxes (Helmken *et al.* 1973; Vishwanath *et al.* 1986; Bhat *et al.* 1987). At energies above 1 TeV there were also reports of emission from the direction of the Crab (Mukanov 1983; Boone *et al.* 1984; Dzikowski *et al.* 1981; Kirov *et al.* 1985), but, because of the limited angular resolution and the absence of accurate timekeeping, it was not possible to identify the source of the observed signal with the nebula or the pulsar. Again there may be conflicting upper limits (Craig *et al.* 1981; Watson 1985). At 100 MeV energies (which are accessible to study by spark chambers on satellites), both a pulsed and steady component were detected (Kniffen *et al.* 1977; Hermsen *et al.* 1977; Clear *et al.* 1987); at 1 GeV the strength of the unpulsed component (which might originate in the nebula or near the pulsar) is 0.25 times that of the pulsed flux.

Using a refined version of the atmospheric Cerenkov technique, we here report the detection of gamma rays above 0.7 TeV from the Crab Nebula at a high level of statistical significance; over the epoch 1986–1988 we find no evidence for variability, and the observed flux is in agreement with that reported previously in 1969–1972 and in an earlier observation utilizing this same technique in 1983–5 (Cawley *et al.* 1985*a*; Gibbs 1987). The observed gamma-ray flux is only 0.2% of the cosmic-ray background. A periodic analysis using the known radio period of the pulsar indicates that less than 25% of the observed signal is pulsed. The detection of such a weak flux from a steady (nonpulsed) source with a significance of 9 standard deviations (σ) is a milestone in the development of ground-based gamma-ray astronomy. It demonstrates the power of using atmospheric Cerenkov shower imaging to distinguish gamma-ray–initiated air showers from those gener-

[1] Harvard-Smithsonian Center for Astrophysics.
[2] St. Patrick's College, Maynooth.
[3] University College, Dublin.
[4] University of Leeds.
[5] Iowa State University.

Some notes on the imaging atmospheric Cherenkov technique:

observations can only be performed on dark* nights

--> low duty cycle ~1000 hours per year

instruments are pointed

--> small** fields of view therefore need targets

no calibration source*** to determine the energy scale

--> rely on simulations to calibrate the instruments

Limitations:

low energy limit

--> local muons, night sky noise

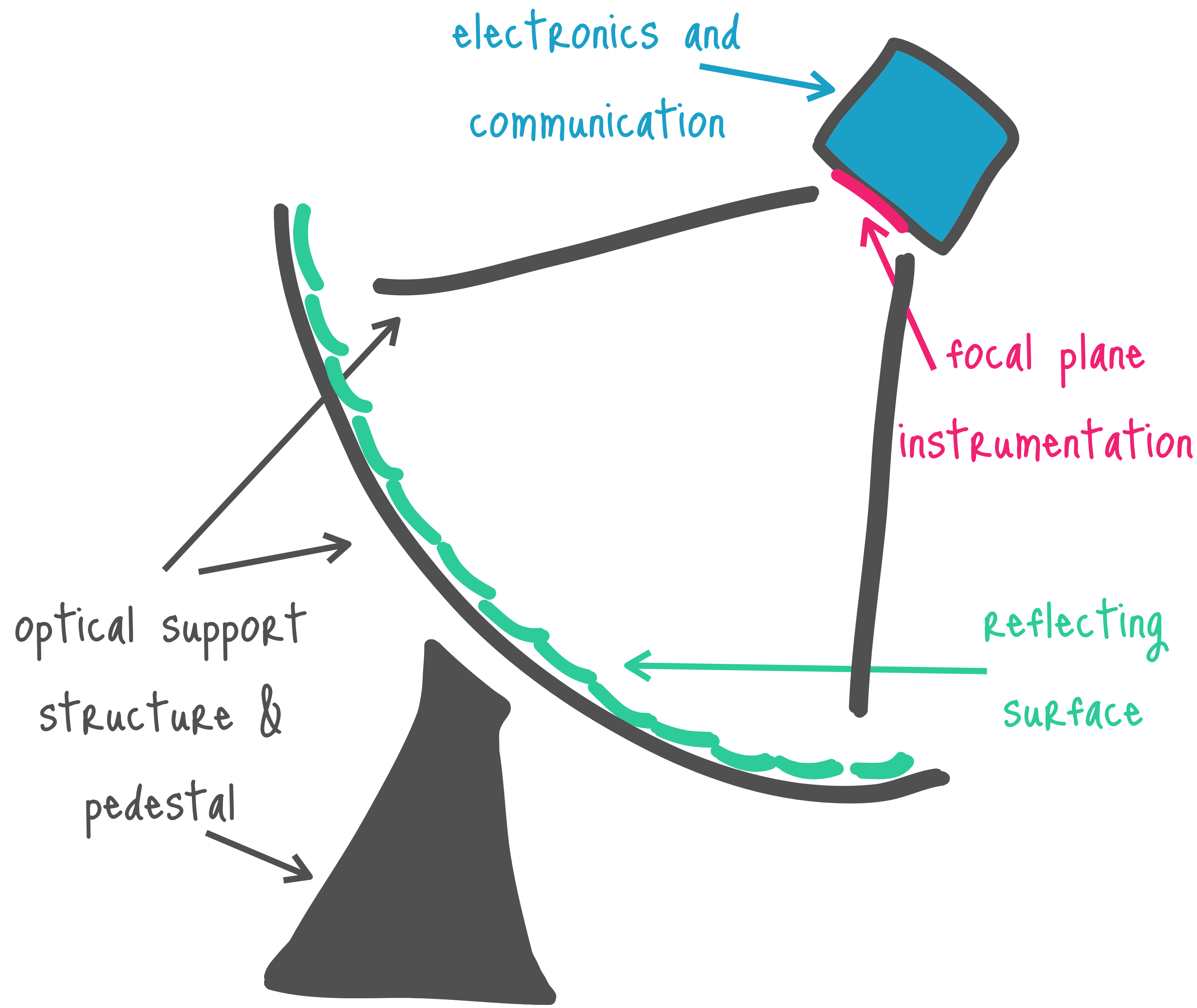
high energy limit

--> collection area

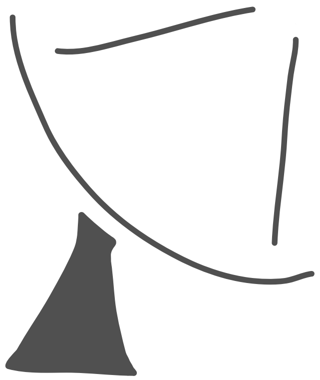
* moon-light observations
** Milagro - "all-sky"
*** Crab - steady?

Anatomy of an IAC Telescope
7/11

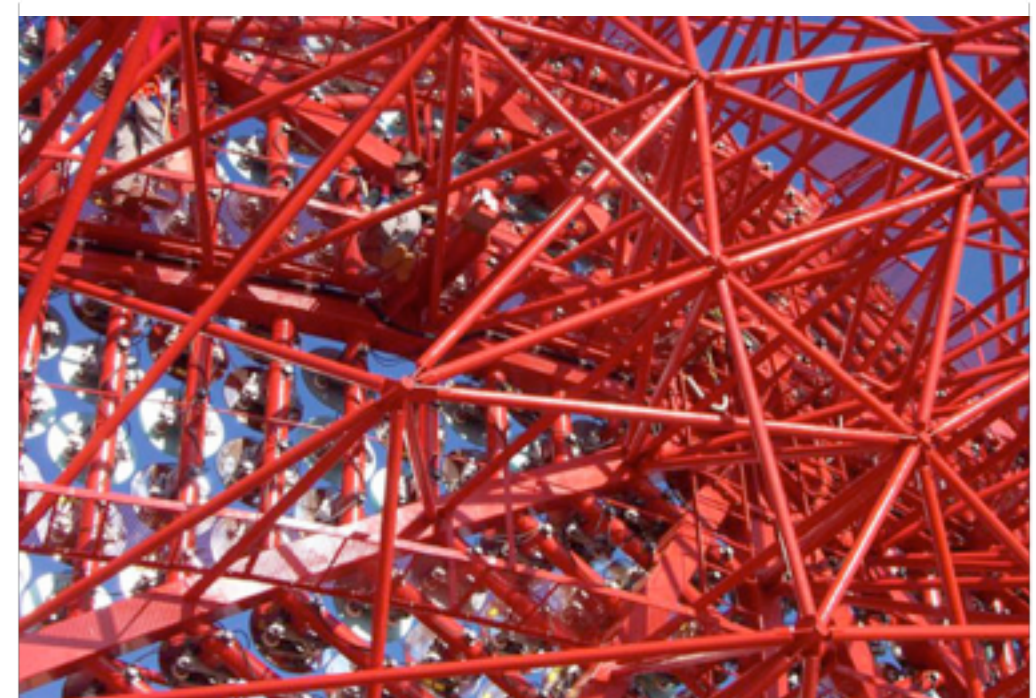
Anatomy of an IAC Telescope



Anatomy of an IAC Telescope



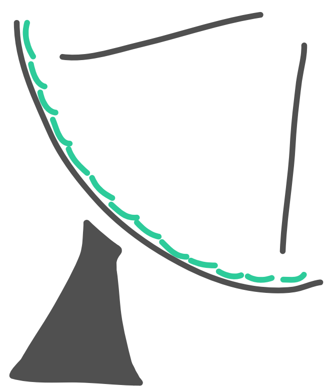
optical support structure & pedestal



STEEL SPACE FRAME - HESS

- often constructed of steel (tubular/steel space frames) but sometimes carbon fibre
- needs to be rigid enough to support the mirror
- no sagging
- thermal expansion
- calibration equipment
- pointing controlled by motors alt-azimuth (azimuth-el) mount often used
  - axes perpendicular to each other
  - one set of motors controls motion about the vertical axis - azimuth
  - a separate set of motors controls motion about the horizontal axis - altitude)

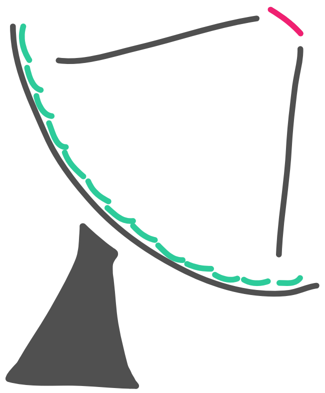
Anatomy of an IAC Telescope



- Davies-Cotton design often used
  - many spherical mirrors provide effectively the same collection area as a large mirror
  - Advantages:
    - all mirror facets are identical
    - easy to align
    - good off-axis performance (superior to parabolic) -> can have larger field of view
  - Drawback
    - transit times from different mirrors are unequal thus introducing a spread of ~6ns in arrival times at focal plane
- Parabolic mirrors are also used - no time spread in arrival of photons at camera

DAVIES COTTON DESIGN - VERITAS

Anatomy of an IAC Telescope



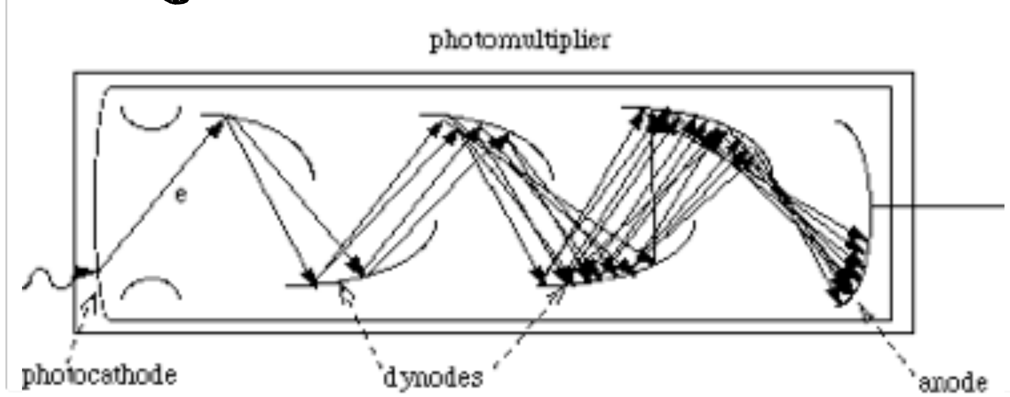
focal plane instrumentation

- All IAC telescopes today use photomultiplier tubes as the detectors*

- vacuum tubes

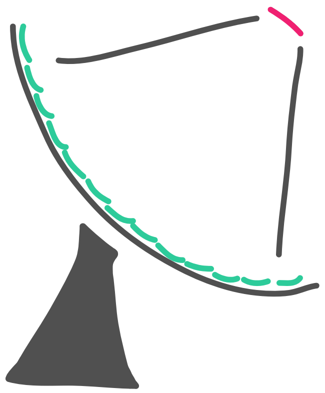
✳ UV - near infrared

- extremely sensitive
- high gain
  ➡ amplify signal by up to 10^8
- low noise
- ultra-fast response
- large collection area



* higher quantum efficiency silicon PMs are under investigation for future detectors
  ➡ FACT currently uses Geiger-mode avalanche photodiodes (astro-ph/1304.1710)

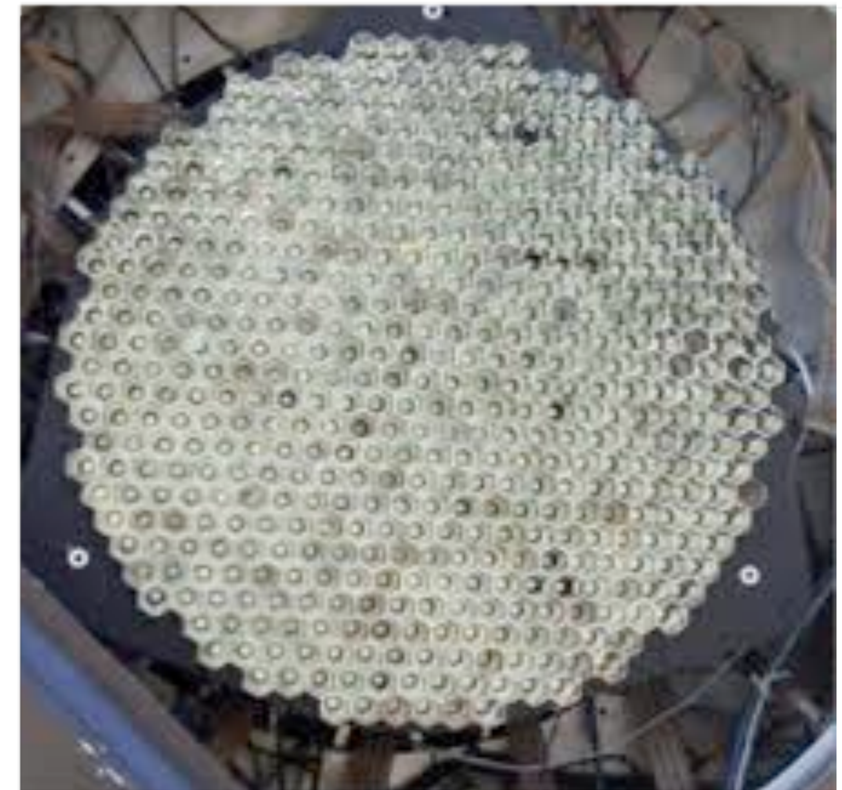
Anatomy of an IAC Telescope



focal plane instrumentation

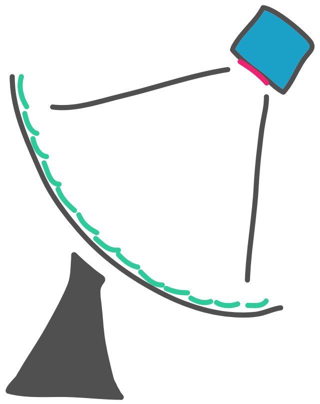
- All IAC telescopes today use photomultiplier tubes as the detectors*
- light cones are used to help recover light that would have been lost between the PMTs
- high voltage (~ 1000 V) needs to be supplied to each of the PMTs

* higher quantum efficiency silicon PMs are under investigation for future detectors
  ➡ FACT currently uses Geiger-mode avalanche photodiodes (astro-ph/1304.1710)



PMT CAMERA & LIGHTCONES
VERITAS

Anatomy of an IAC Telescope



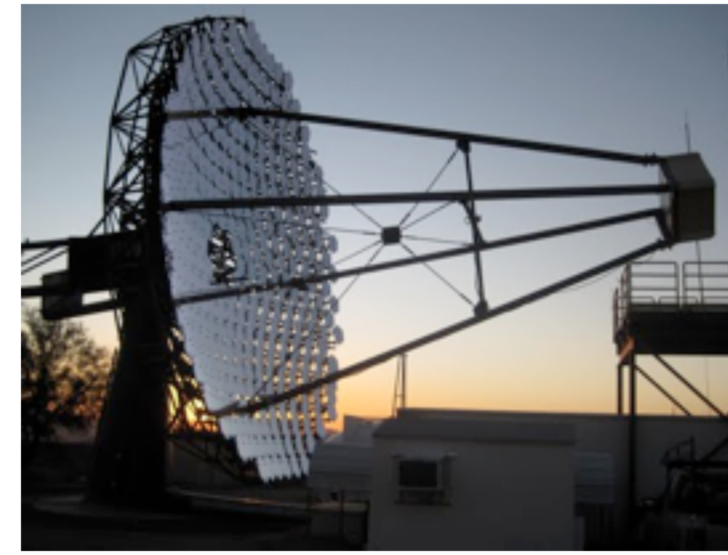
electronics and communication

- the signals from the PMTs need to be transmitted to the trigger electronics to decide whether to record a given event and then digitize it
  - sometimes trigger logic is housed in the focal plane
  - sometimes in "counting building" ... in this case, signal is often amplified before transmission to trigger electronics
- trigger consists of at least two levels
  - Level 1: individual PMT
  - Level 2: telescope ... "pattern trigger" - expect neighbouring PMTs to trigger if it is a real gamma-ray signal
  - Level 3: array trigger - when have more than one telescope, can make intelligent array-level trigger where decision on whether to record a particular event is based on how it looks in all telescopes

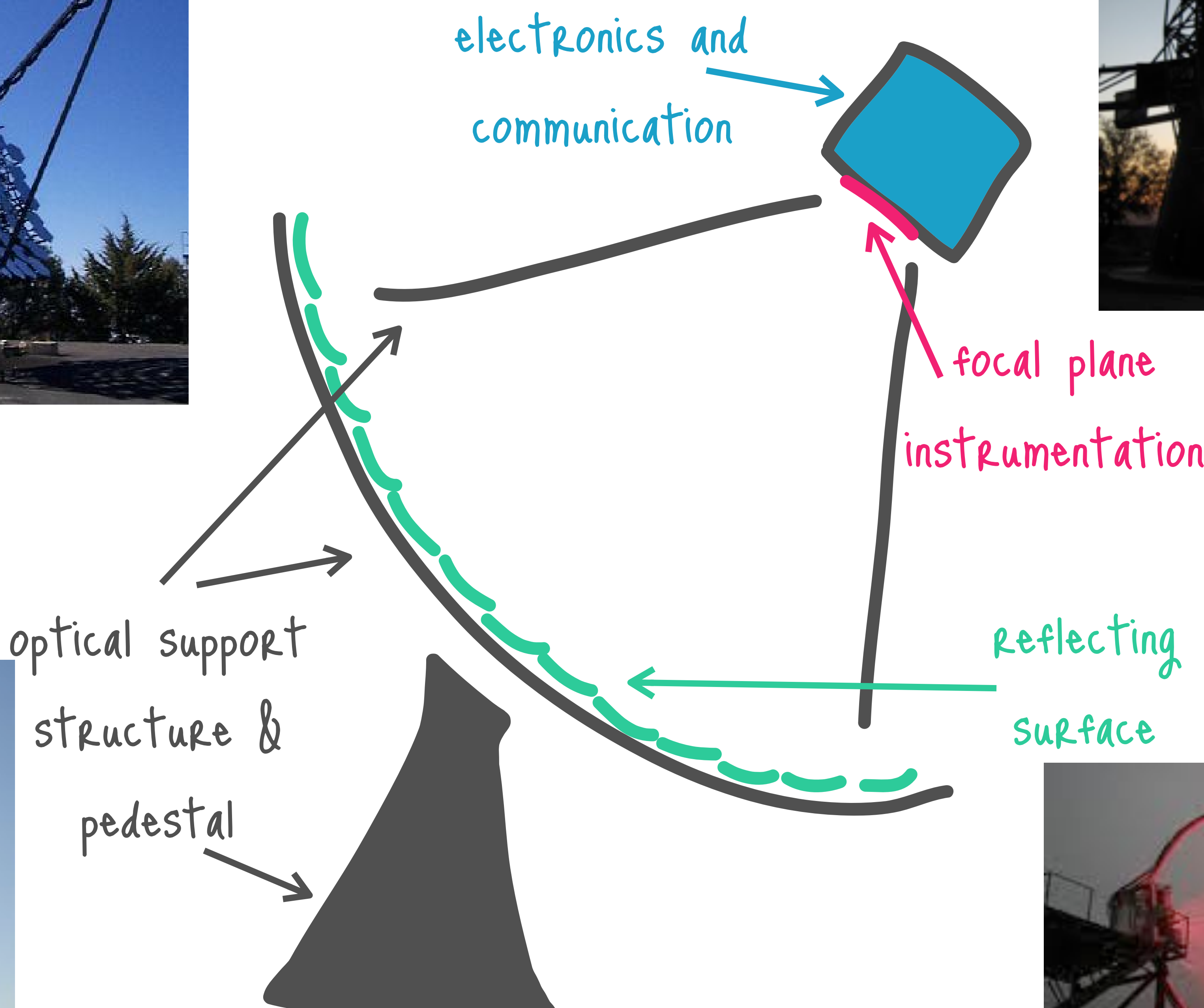
[data-analysis is done offline]

Anatomy of an IAC Telescope

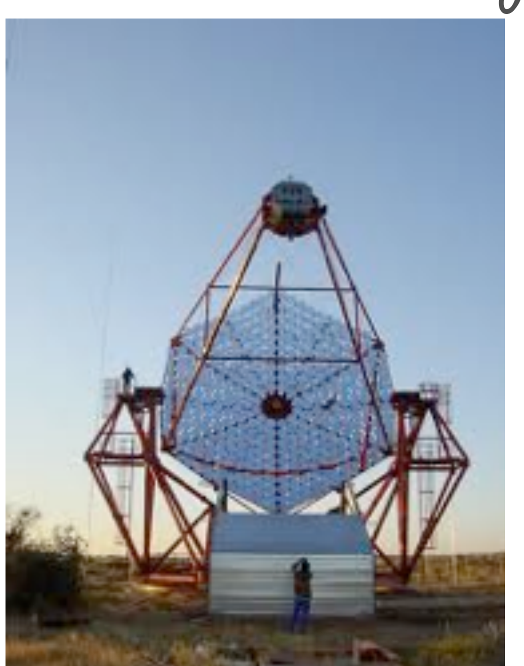
WHIPPLE



VERITAS



H.E.S.S.



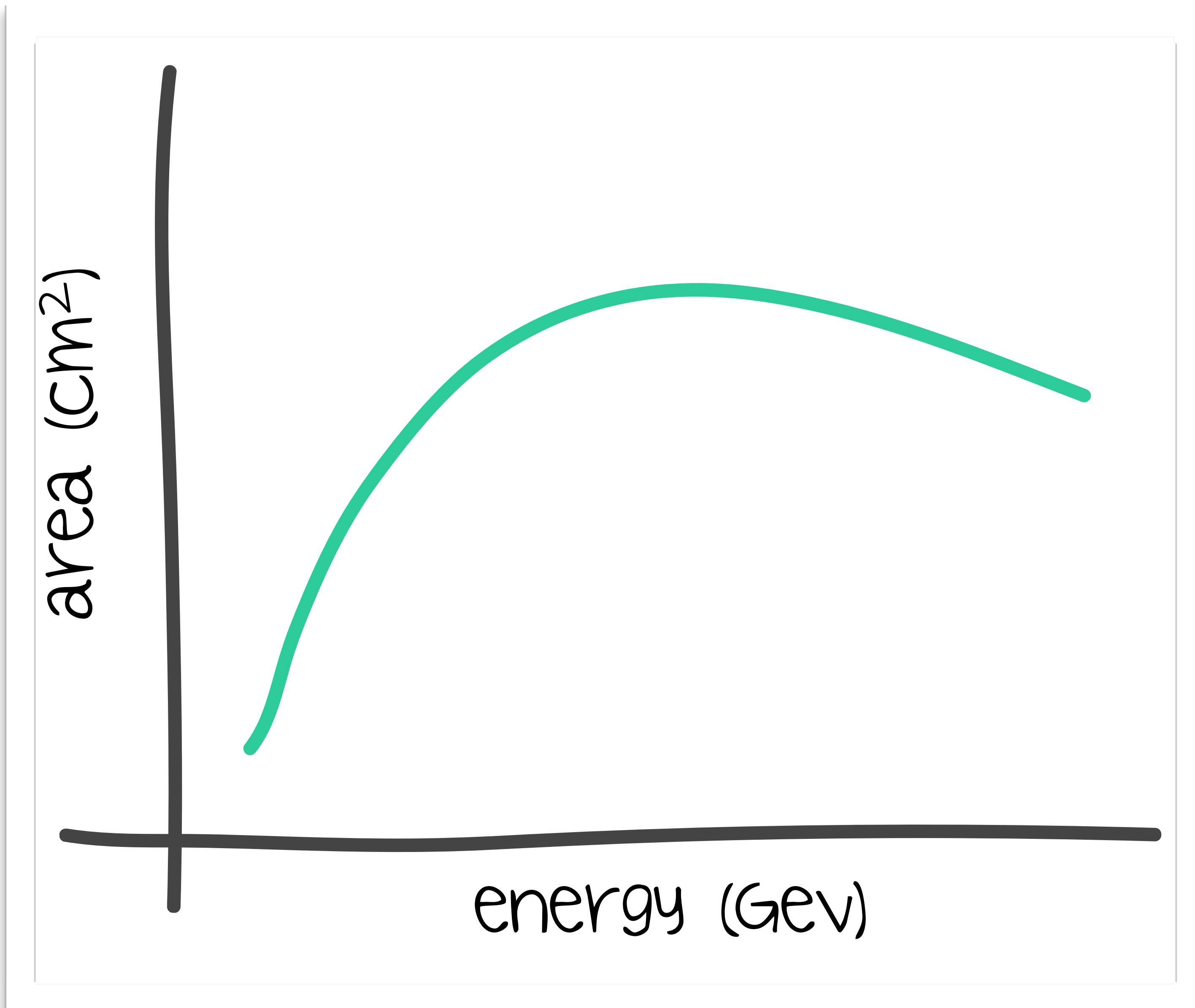
MAGIC

Terminology

8/11

Terminology

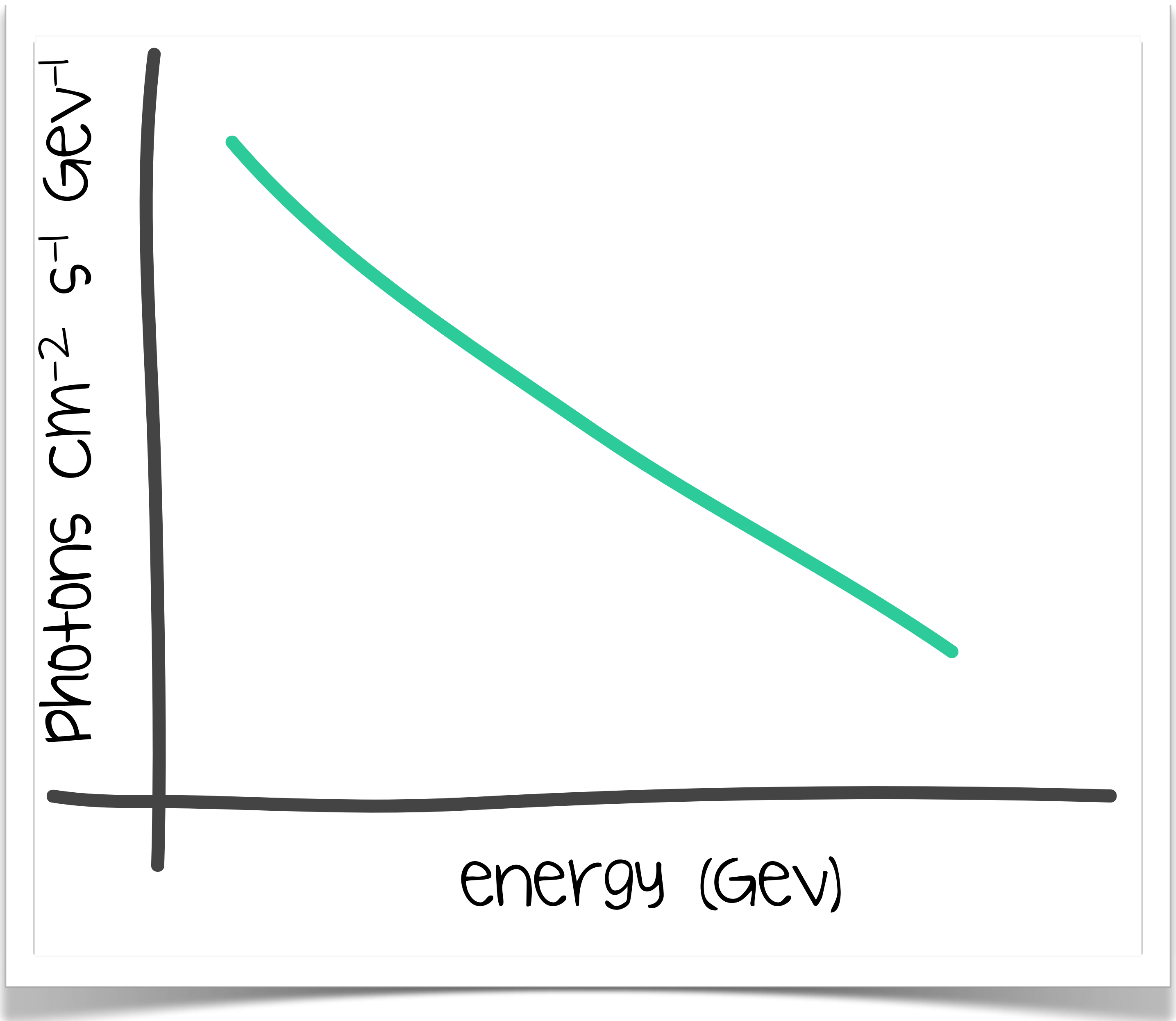
COLLECTION AREA



- derived from simulations
- tells you how large the collection area of your telescope is at each energy after your gamma-ray selection criteria have been applied
  - ➡ **i.e. gives you the "cm^{-2}" part of your rate**
  - **… X gammas cm^{-2} s^{-1}**

Terminology

ENERGY SPECTRUM

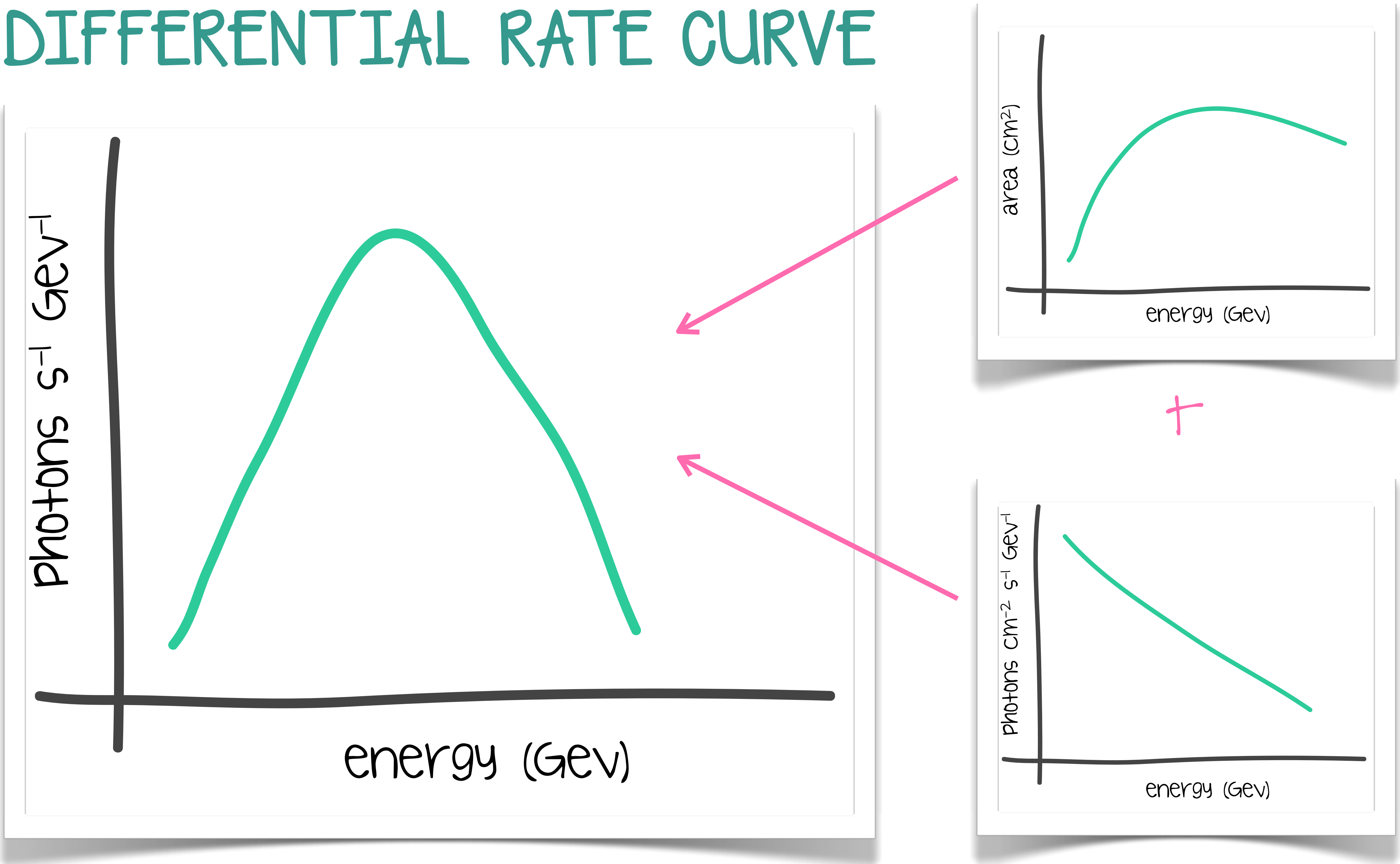


- gammas cm^{-2} s^{-1} GeV^{-1} at each energy

  ➡differential spectrum

Terminology

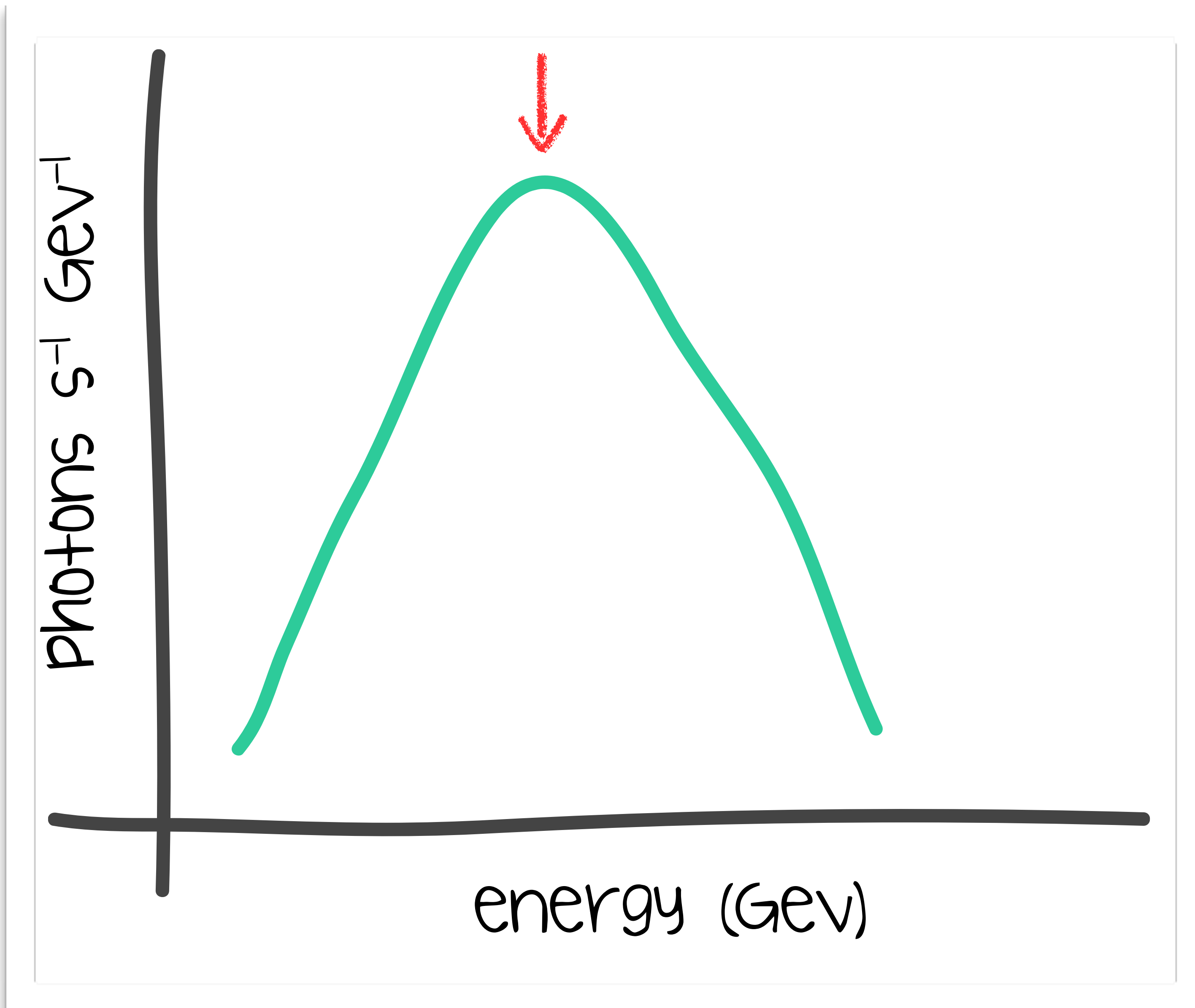
DIFFERENTIAL RATE CURVE



... fold the acceptance area curve with a source spectrum to get the differential rate curve

Terminology

ENERGY THRESHOLD



- from the differential rate curve can determine energy at which telescope is most efficient at detecting gamma rays
- often called "energy threshold"
  - ➡ misleading term ... telescopes have significant collection area below this value
- "Peak response energy" is perhaps a more accurate name
- *When you hear the term "energy threshold" make sure you know what is being referred to*

Second Generation Telescopes
9/11

Second Generation Telescopes

The imaging atmospheric Cherenkov technique enabled the detection of the Crab nebula, thus establishing VHE gamma-ray astronomy as a viable new field

Imaging Atmospheric Cherenkov Telescopes (IACTs) were constructed at other locations around the world

In recognition of his contribution to the field of very-high-energy astrophysics, Trevor Weekes was awarded the Rossi prize* in 1997

> "The 1997 Rossi Prize of the High Energy Division of the American Astronomical Society is awarded to Trevor C. Weekes for his key role in the development of very high energy gamma-ray astronomy and the discovery of TeV gamma radiation from the Crab nebula and Mrk 421."

*The Rossi Prize is awarded by the High Energy Astrophysics Division of the American Astronomical Society annually in honor of Bruno Rossi "for a significant contribution to High Energy Astrophysics, with particular emphasis on recent, original work."

Second Generation Telescopes

"Second generation" instruments: 1989 - ~2003

Seven TA
Utah, USA

CAT
Themis, France

Whipple
Arizona, USA

HEGRA
La Palma, Canary Islands

CANGAROO
Woomera, Australia

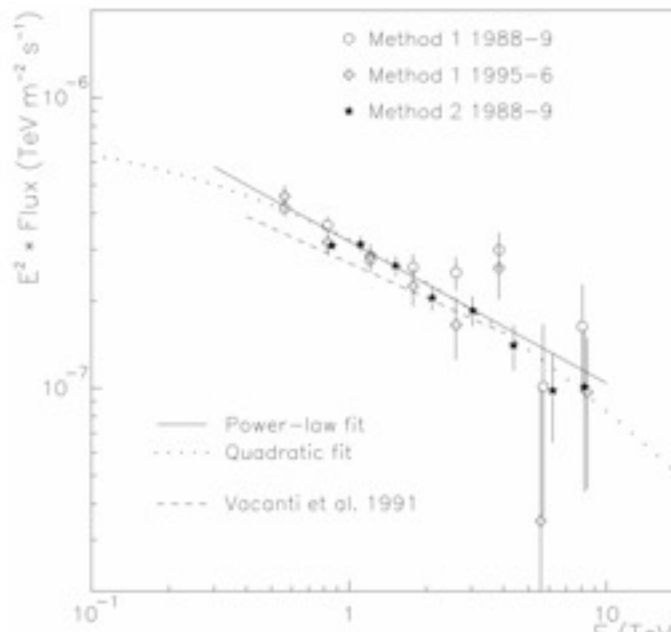
Second Generation Telescopes

Some highlights of the early days of discovery – each new SOURCE was a big deal

1989: Discovery of the Crab Nebula

- first ever TeV source (confirmed by HEGRA in 1996), spectrum in 1998

NASA Composite Image



Hillas et al. ApJ, 503, 744 (1998)

the "standard candles" for years in TeV astronomy

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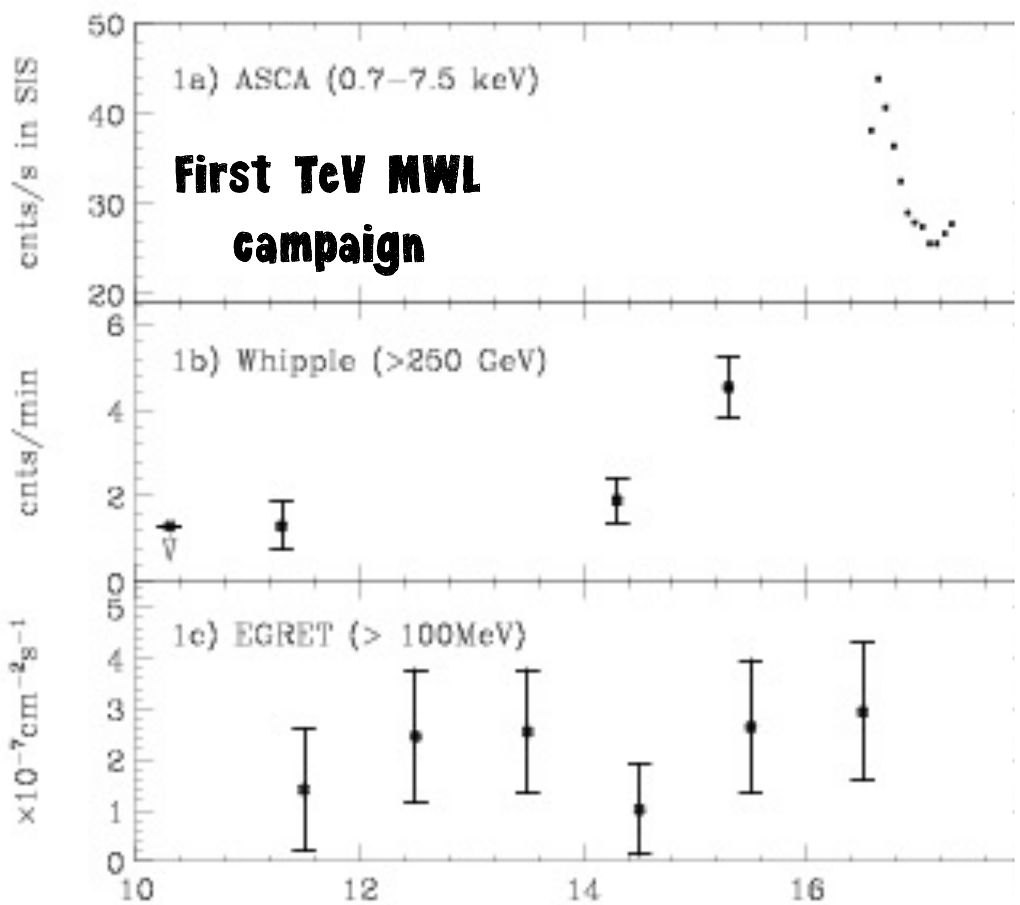
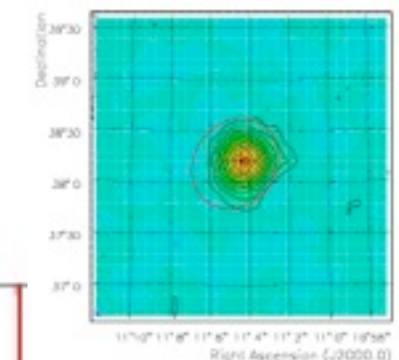
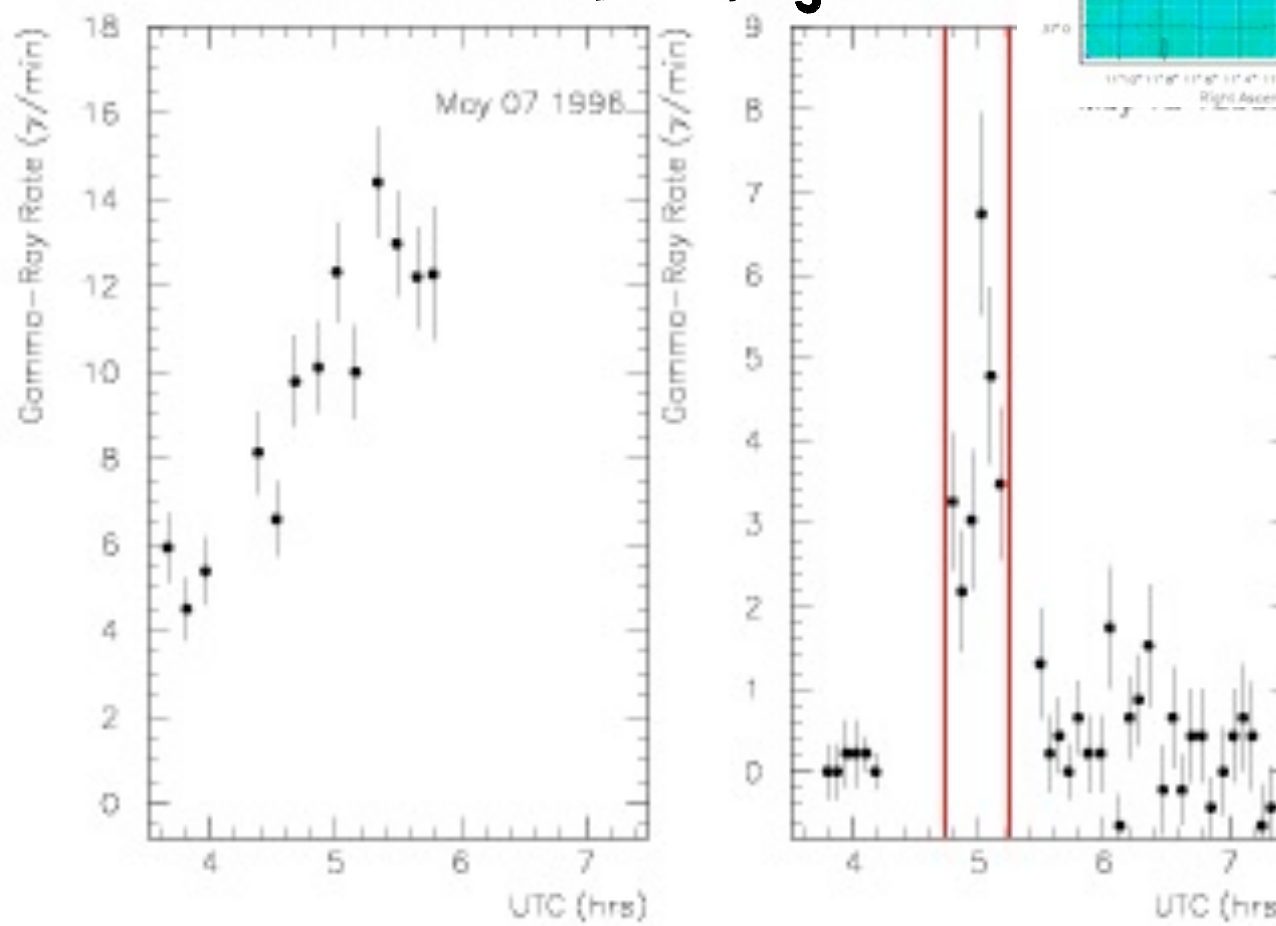


Takahashi, Madejski & Hidetoshi, AstroPart; Phys. 11, 177 (1994)

Fastest (first!) TeV Flaring





Buckley et al., ApJ, 472, L9

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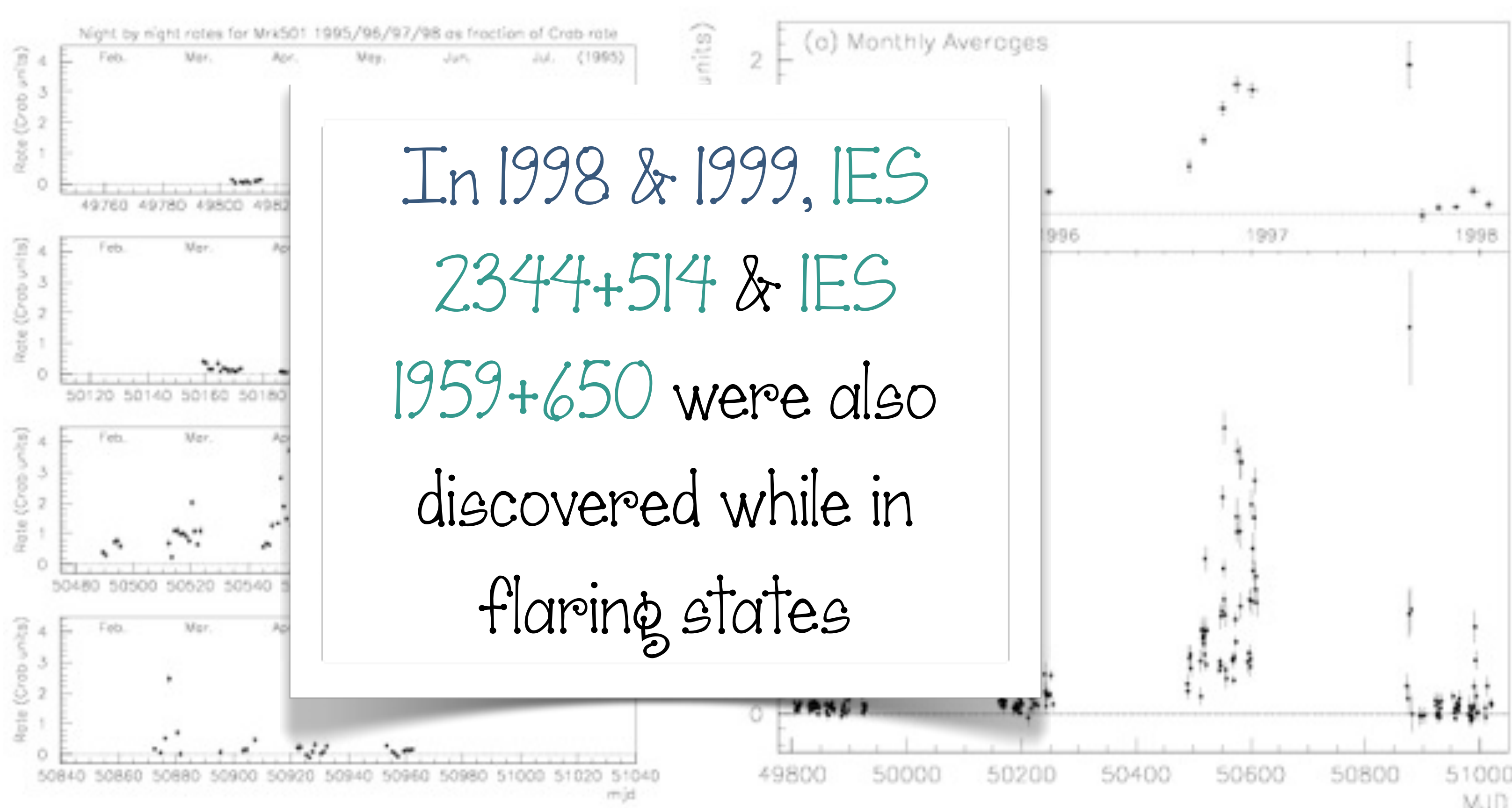
1996: Discovery of TeV gamma rays from Markarian 501

- first ever gamma-ray source to be DISCOVERED at TeV energies

Largest variability ever seen at these energies!



QUINN ET AL., APJ, 518, 693 (1999)

In 1998 & 1999, IES 2344+514 & IES 1959+650 were also discovered while in flaring states

Second Generation Telescopes

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2001: Discovery of TeV gamma rays from Cassiopeia A

- was the weakest source detected at the time (3.3% Crab)

COMPOSITE SPITZER, CHANDRA, HUBBLE

Second Generation Telescopes

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- first ever source in the Southern Hemisphere

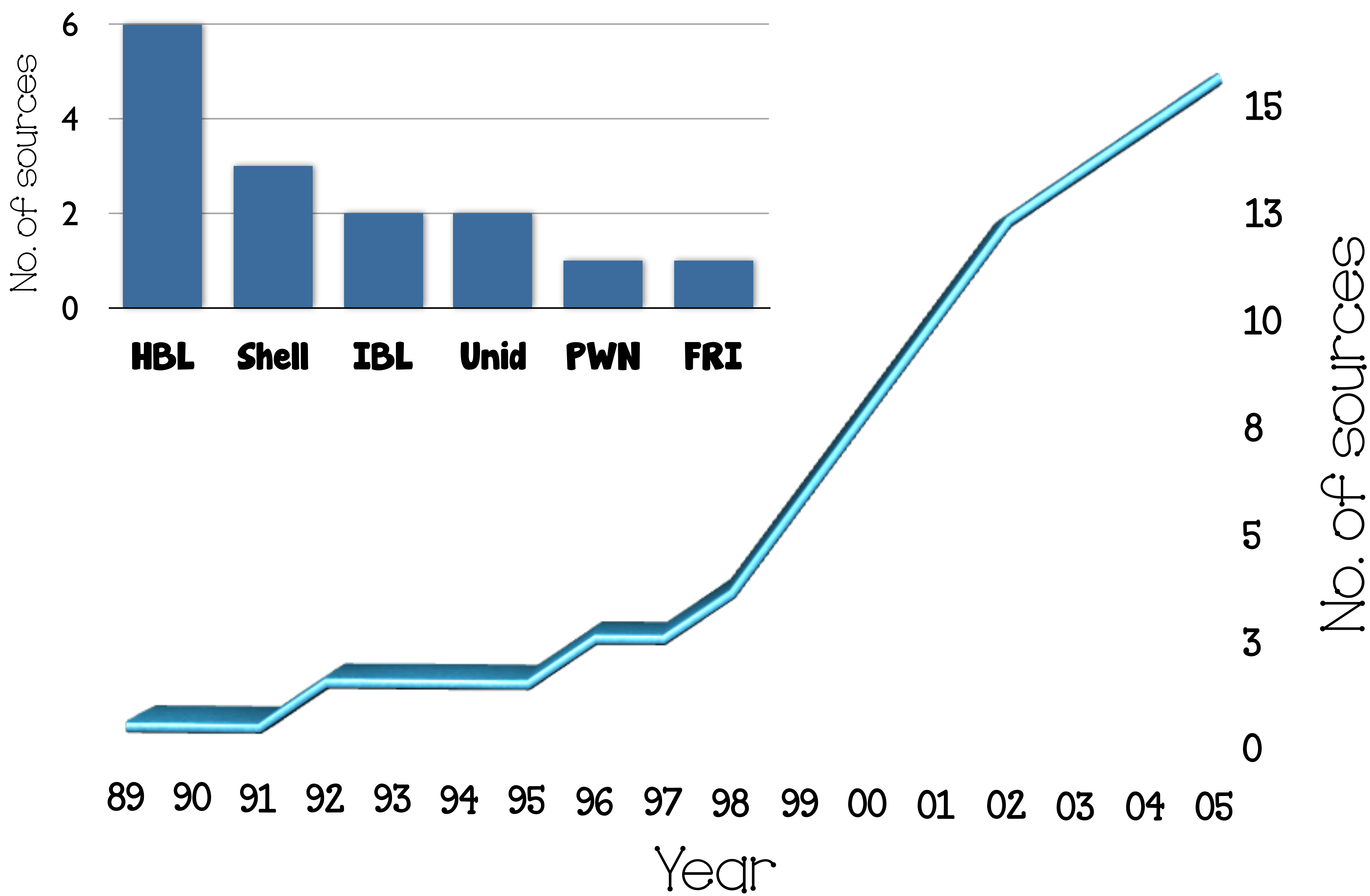
2001: Discovery of TeV gamma rays from Cassiopeia A

- was the weakest source detected to date (3.3% Crab)

2002: Discovery of TeV gamma rays from H1426+428

- was the most distant source yet detected, z=0.129

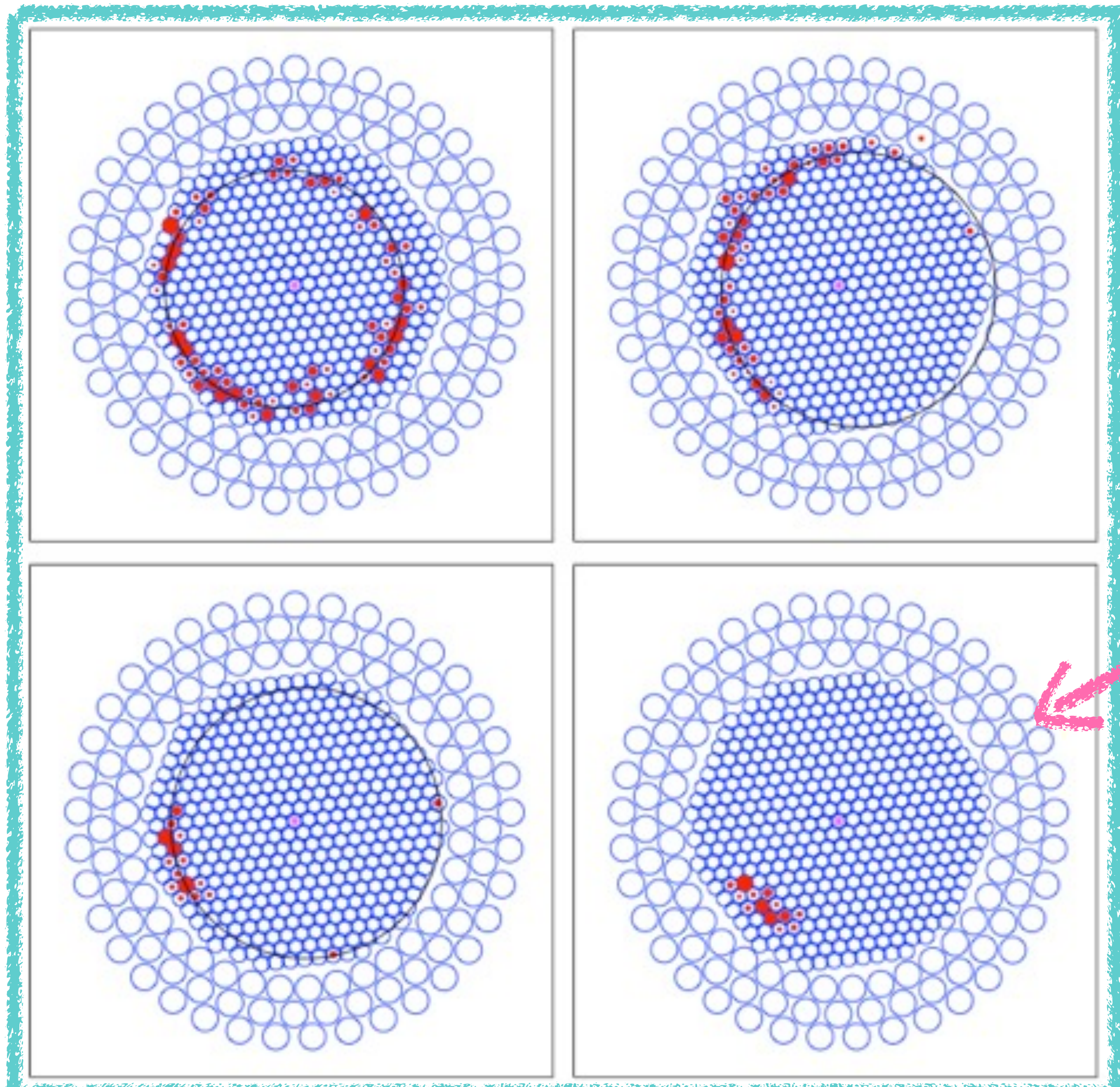
Second Generation Telescopes



Second Generation Telescopes

Muons produced (mostly) in hadronic showers from pion decay

- do not interact strongly with matter so a large proportion reach the earth's surface
  - ➡ the "penetrating component" of cosmic rays



REAL & SIMULATED MUONS WITH DIFFERENT IMPACT PARAMETERS

Cherenkov light from local muons is indistinguishable from a low-energy gamma-ray shower

Second Generation Telescopes

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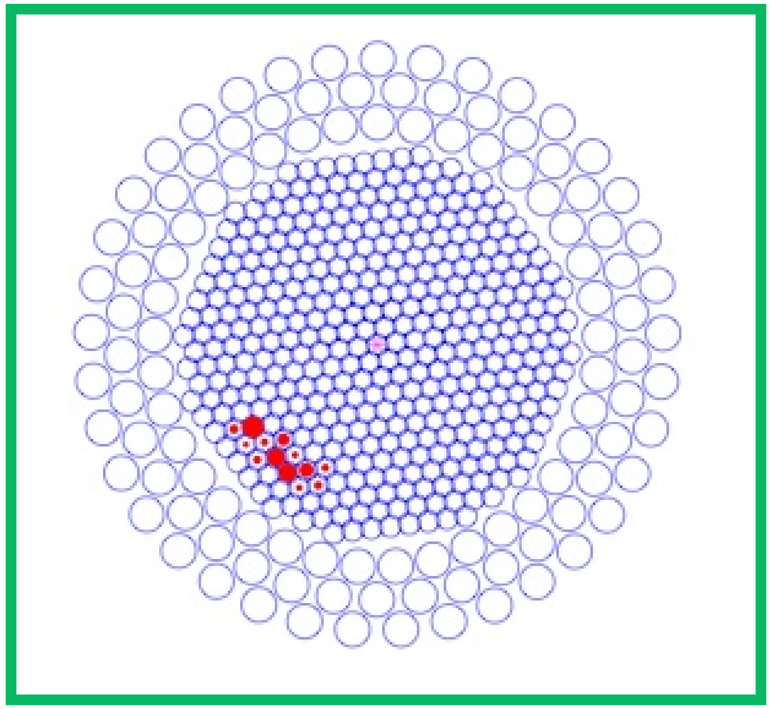
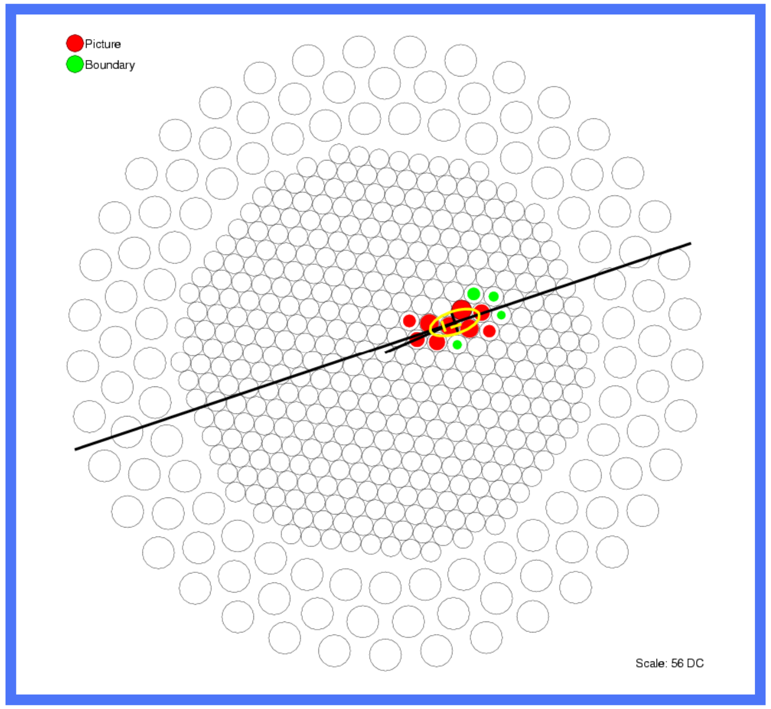
- do not interact strongly with matter so a large proportion reach the earth's surface
  - ➡ the "penetrating component" of cosmic rays



partial muon

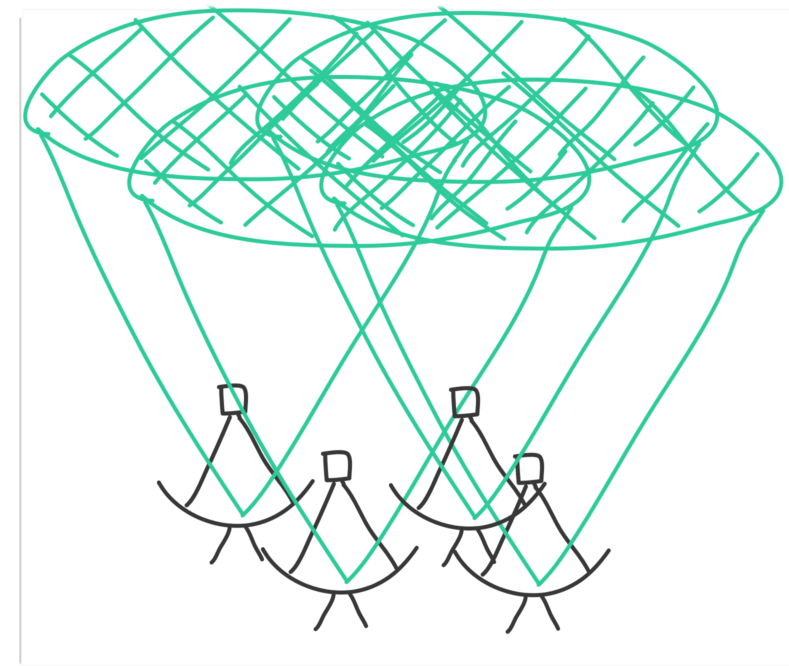


gamma ray

Third Generation Telescopes
10/11

Third Generation Telescopes

The success of Whipple, HEGRA, CAT and CANGAROO led to a growth in the field of ground-based gamma-ray astronomy. New instruments were developed (and the teams of people building them grew too).



- arrays*
- larger energy range
- more sensitive
- better energy resolution
- higher angular resolution

* HEGRA was an array; MAGIC was a single-telescope system at first

Third Generation Telescopes

"Third generation" instruments: ~2003 - present

VERITAS

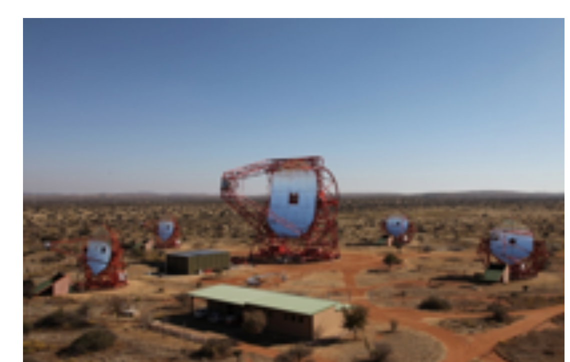
Arizona, USA

MAGIC

La Palma, Canary Islands

HESS

Khomas Highlands, Namibia



HAWC*

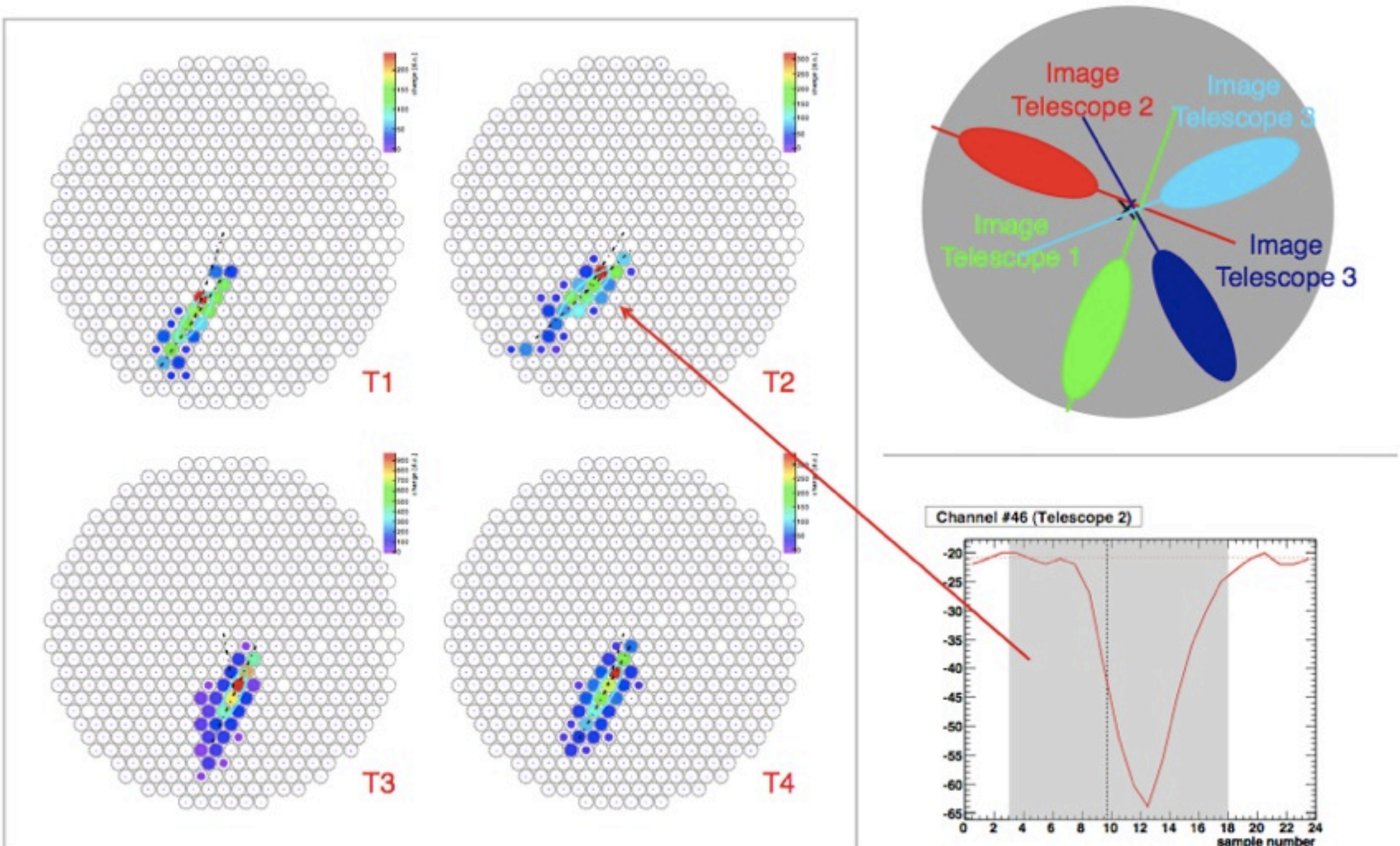
Sierra Negra, Mexico

not yet in operation

*Water Cherenkov

Third Generation Telescopes

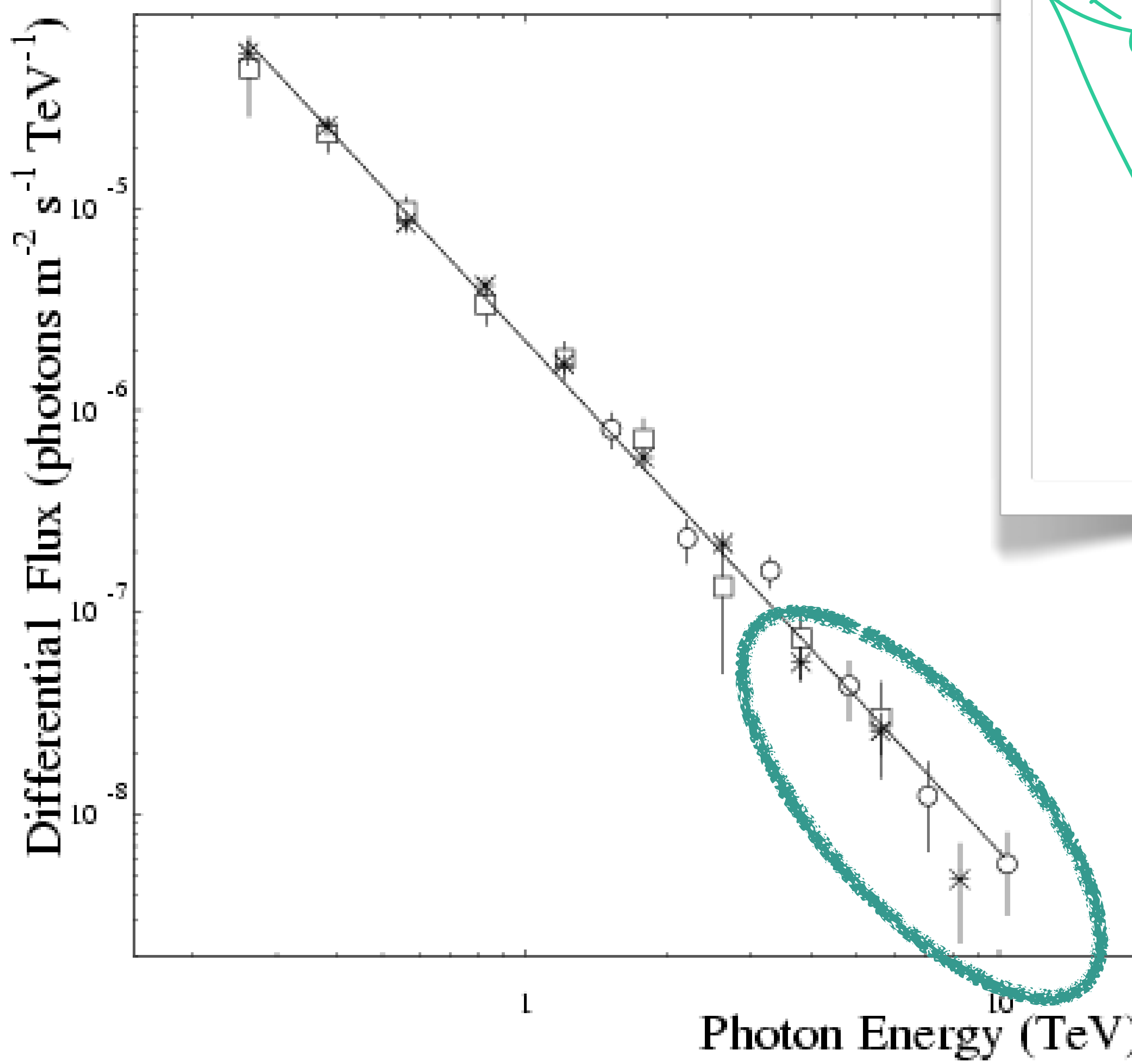
Stereo observations enable us to distinguish local muons from low-energy gamma rays
... multi-telescope trigger requirement helps us operate with lower energy threshold

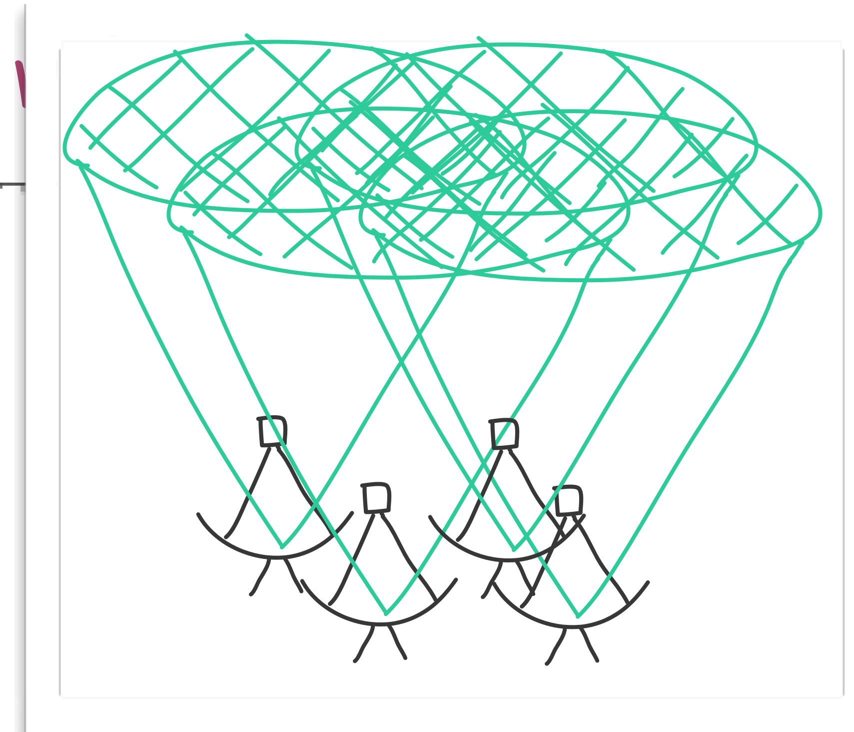


2 ns FADC, 5.5 dc/p.e.

Third Generation Telescopes

the gamma-ray spectra of all sources fall rapidly w



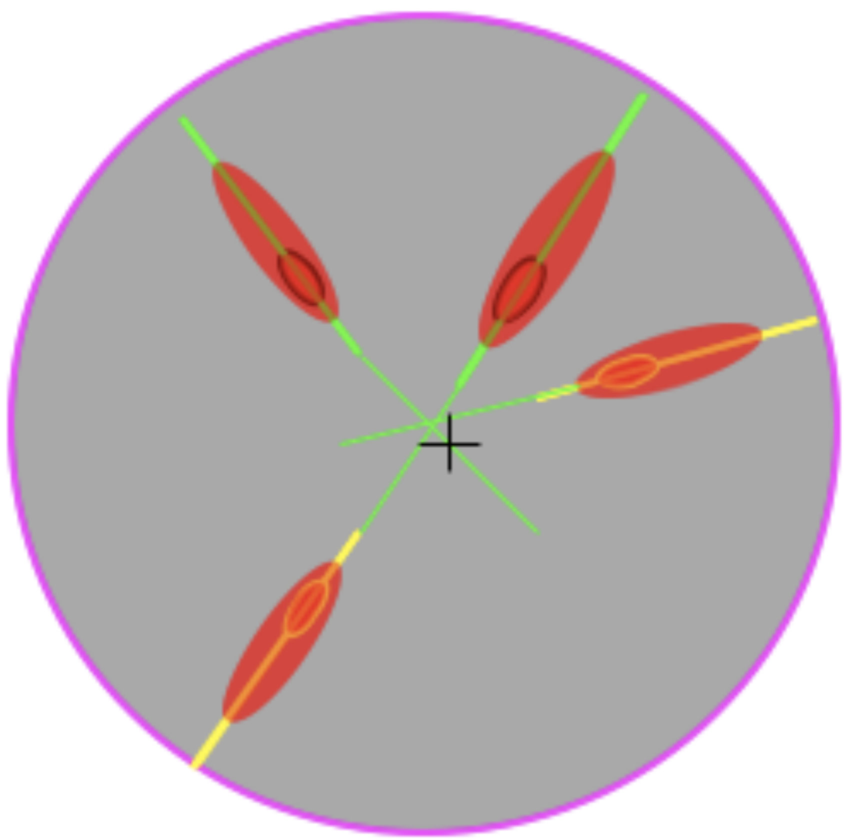


in order to gather as many of the highest energy particles as possible, we must increase the collection area

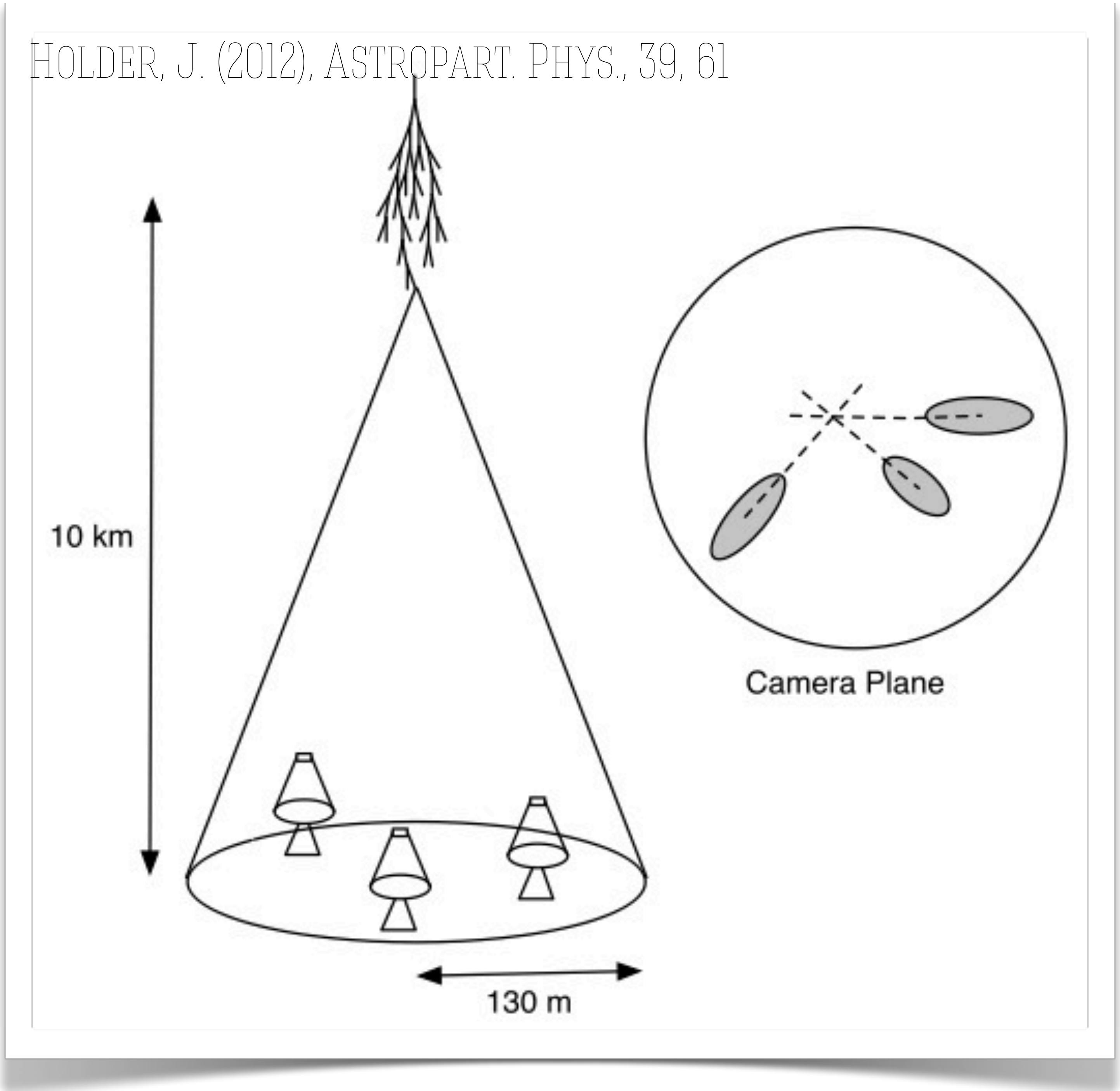
Third Generation Telescopes

Stereo observations enable us more accurately characterise the properties of the gamma rays

More than one (up to 4) image of each shower



Position on Sky



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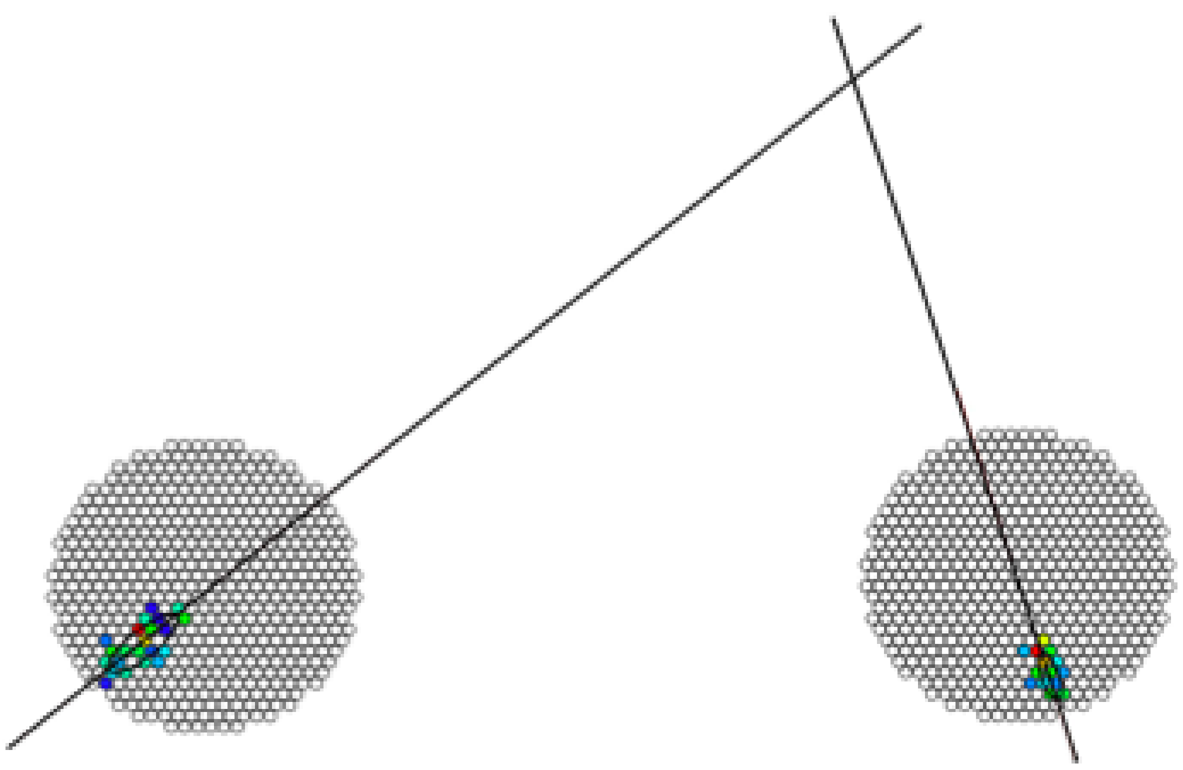
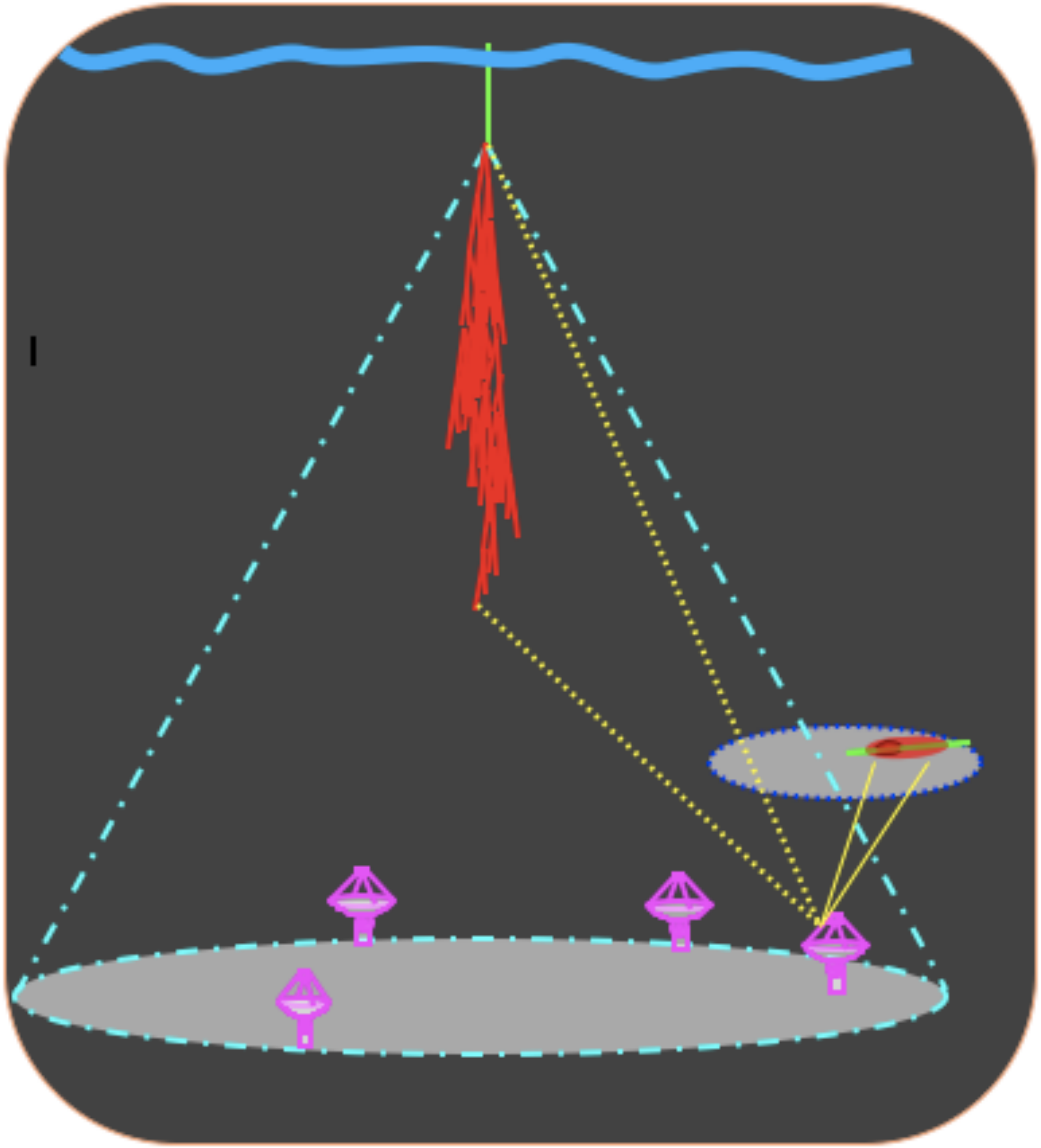


Core location on the ground



Third Generation Telescopes

Some highlights of third generation instruments:

2005: HESS Sky survey

- first published in 2005 with 14 sources … since then has grown to include almost 60 sources

WWW.MPI-HD.MPG.DE

Third Generation Telescopes

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2005: HESS Sky survey

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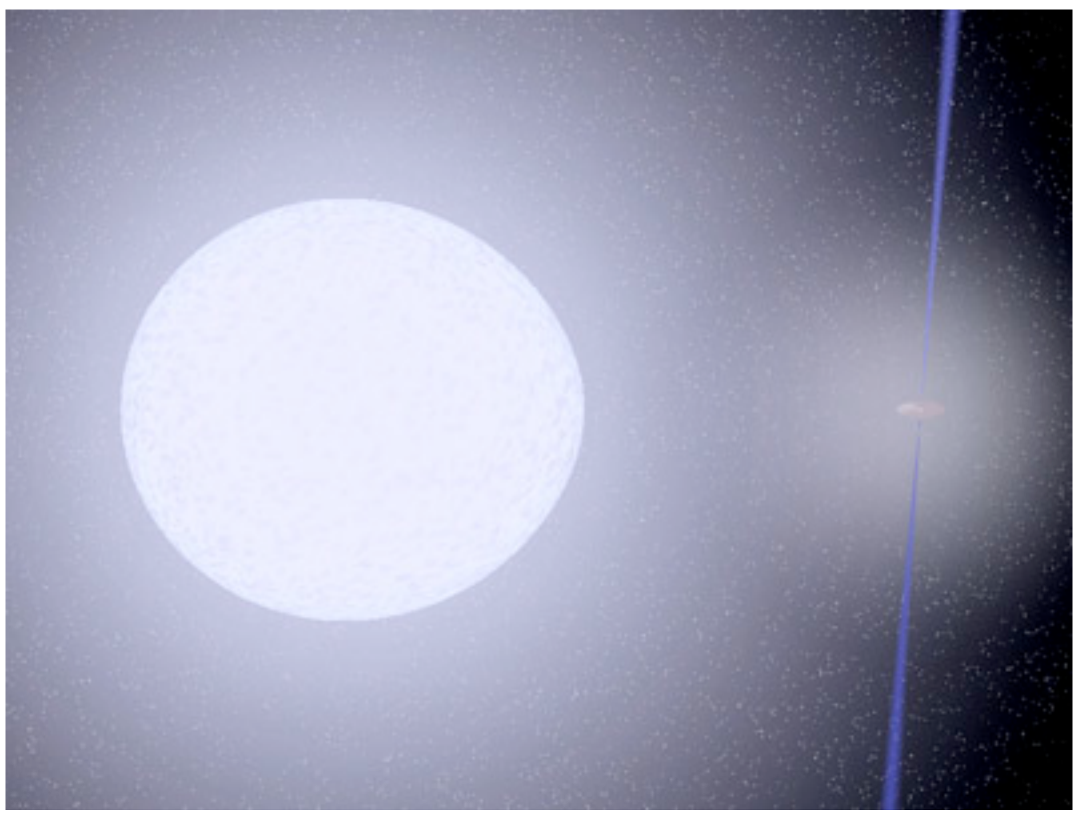
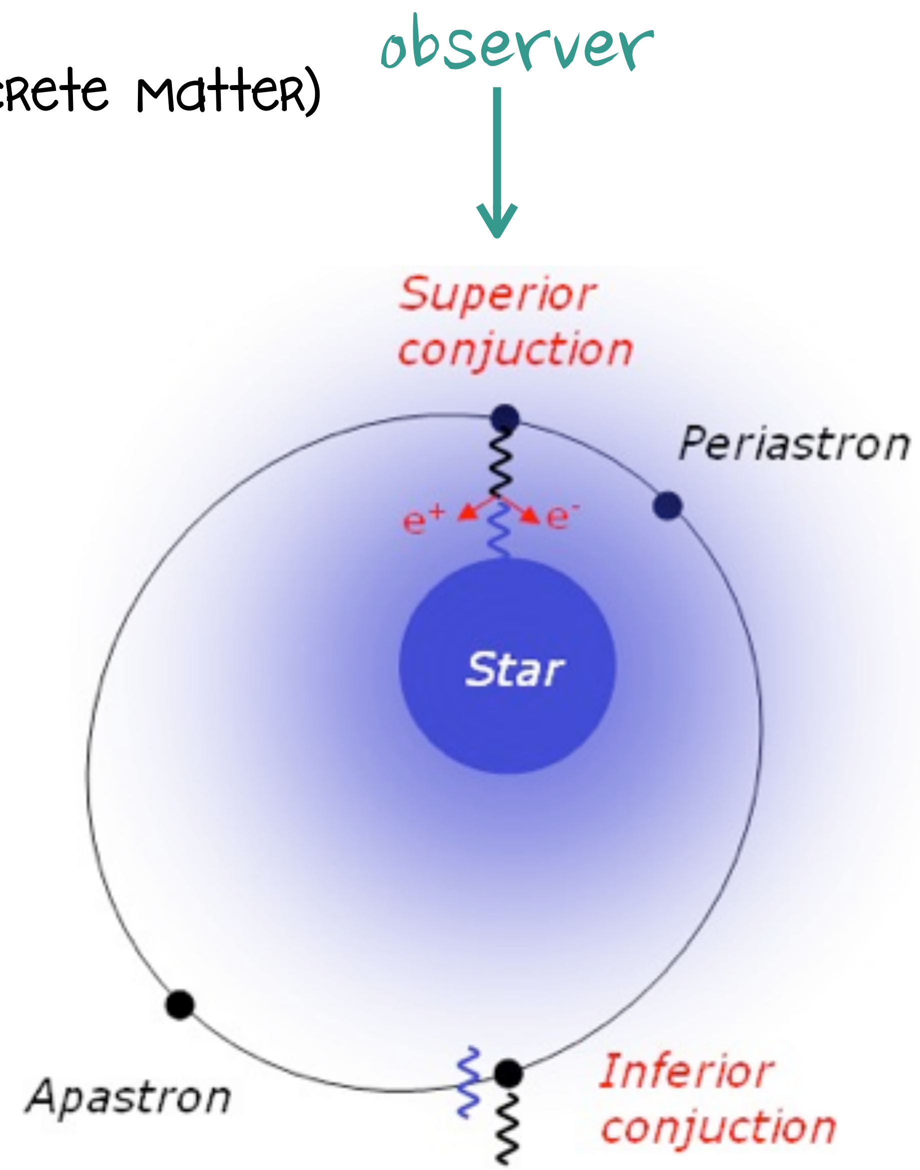
2005: LS 5039 … first gamma-ray binary

- a microquasar (galactic stellar-mass objects that accrete matter)





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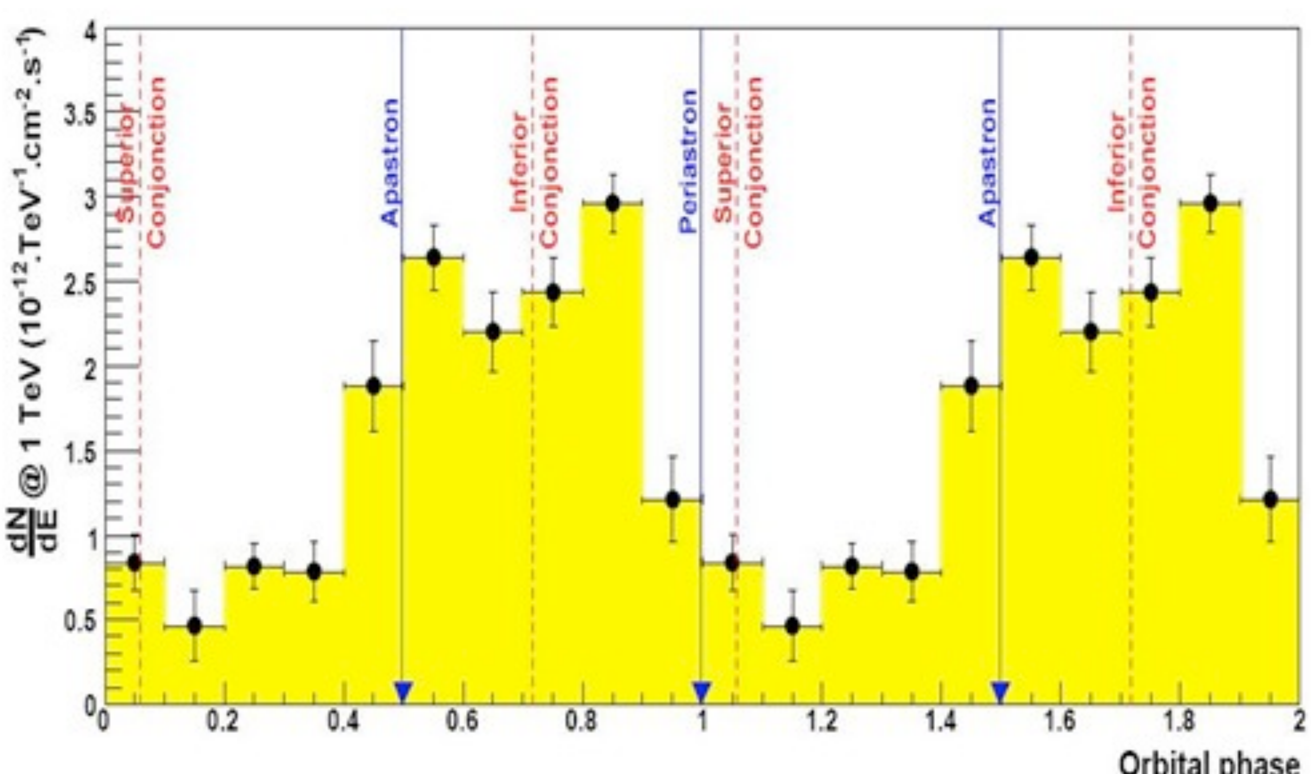
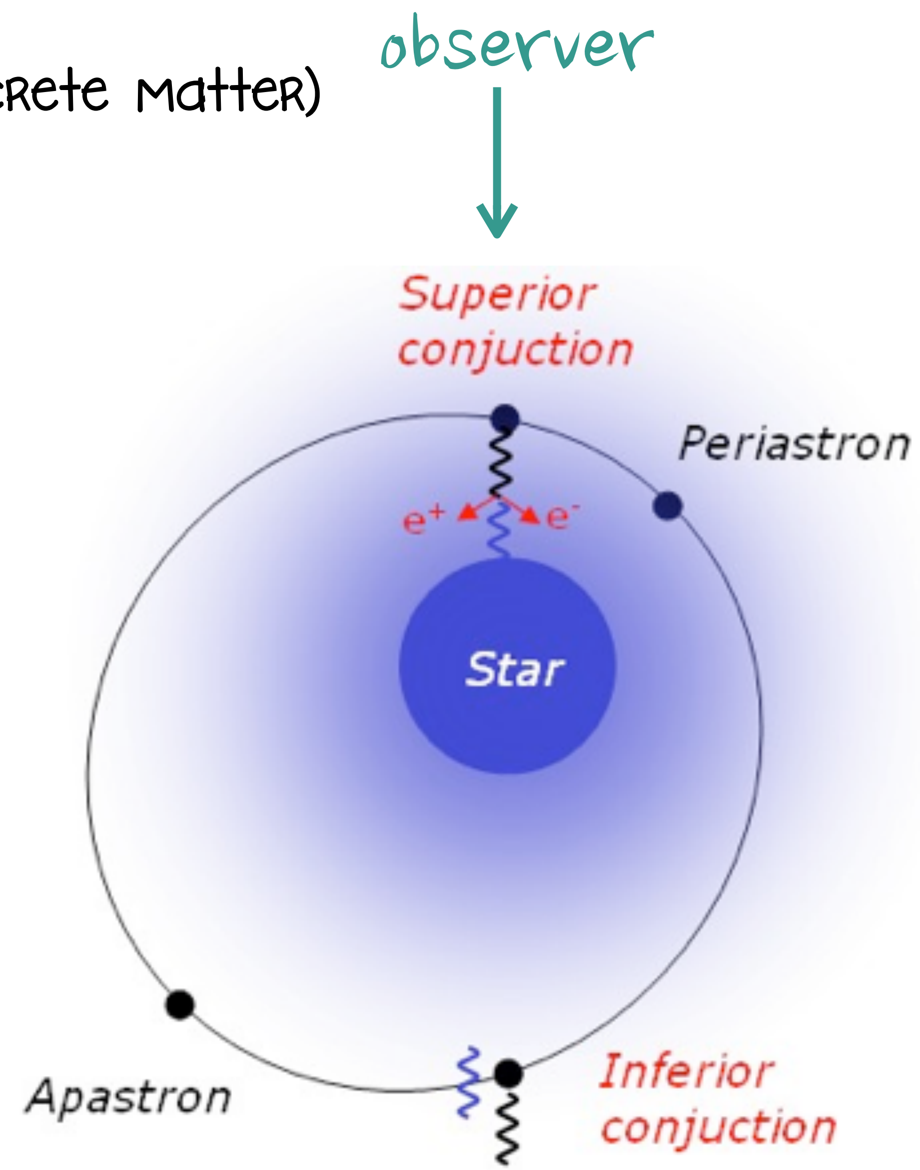


periodicity of signal established (2006)



WWW.MPI-HD.MPG.DE

Third Generation Telescopes

Some highlights of third generation instruments:

2005: HESS Sky survey

- first published in 2005 with 14 sources ... since then has grown to include almost 60 sources

2005: LS 5039 ... first gamma-ray binary

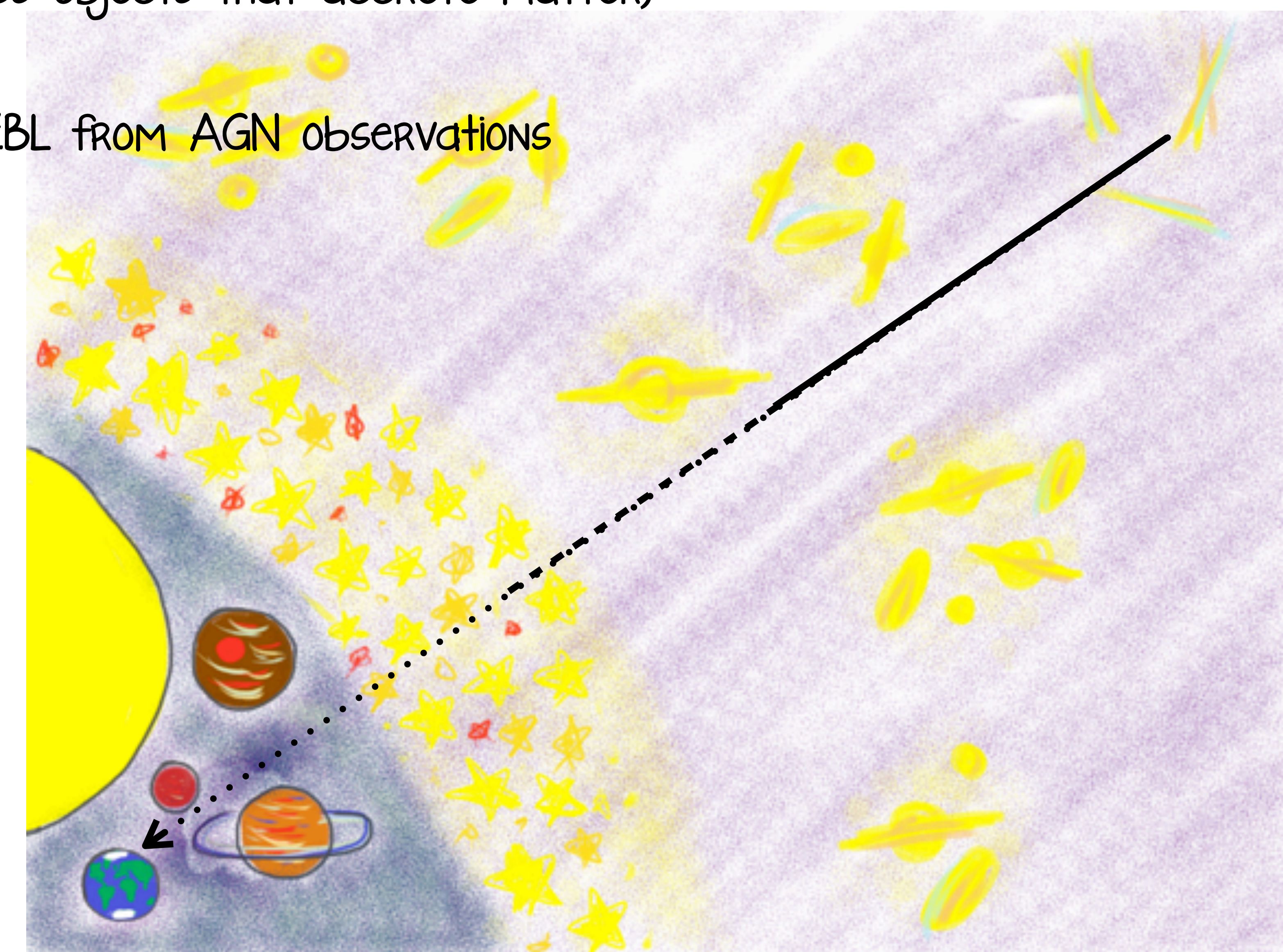
- a microquasar (galactic stellar-mass objects that accrete matter)

2006: Extragalactic background light

- constraints on the density of the EBL from AGN observations

PAIR PRODUCTION

$$\gamma_{TeV} + \gamma_{IR} \rightarrow e^{+} e^{-}$$



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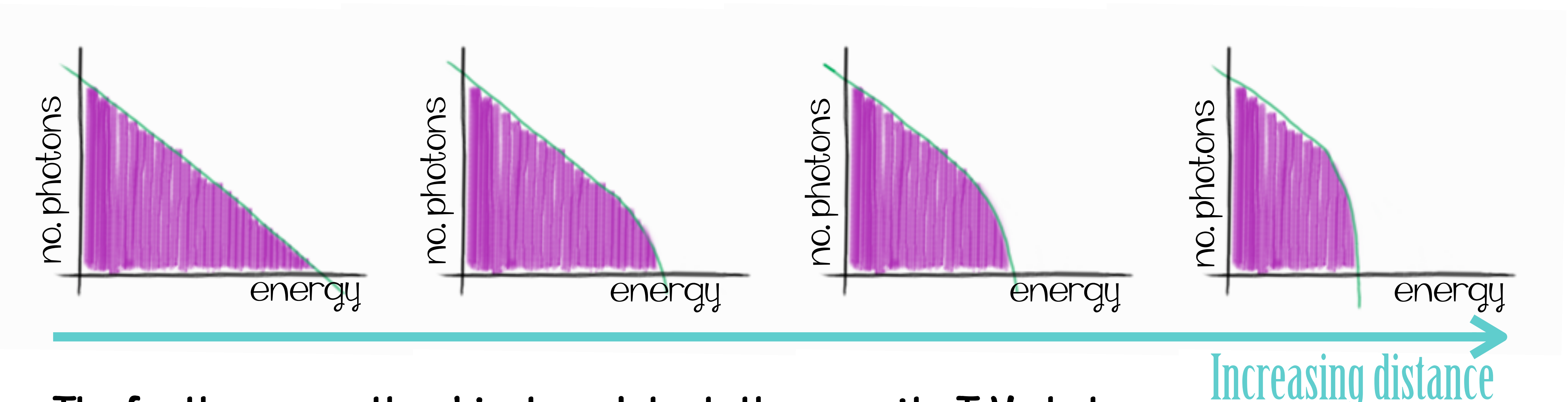

The further away the object we detect, the more its TeV photons are absorbed by the EBL - this results in a break in the spectrum

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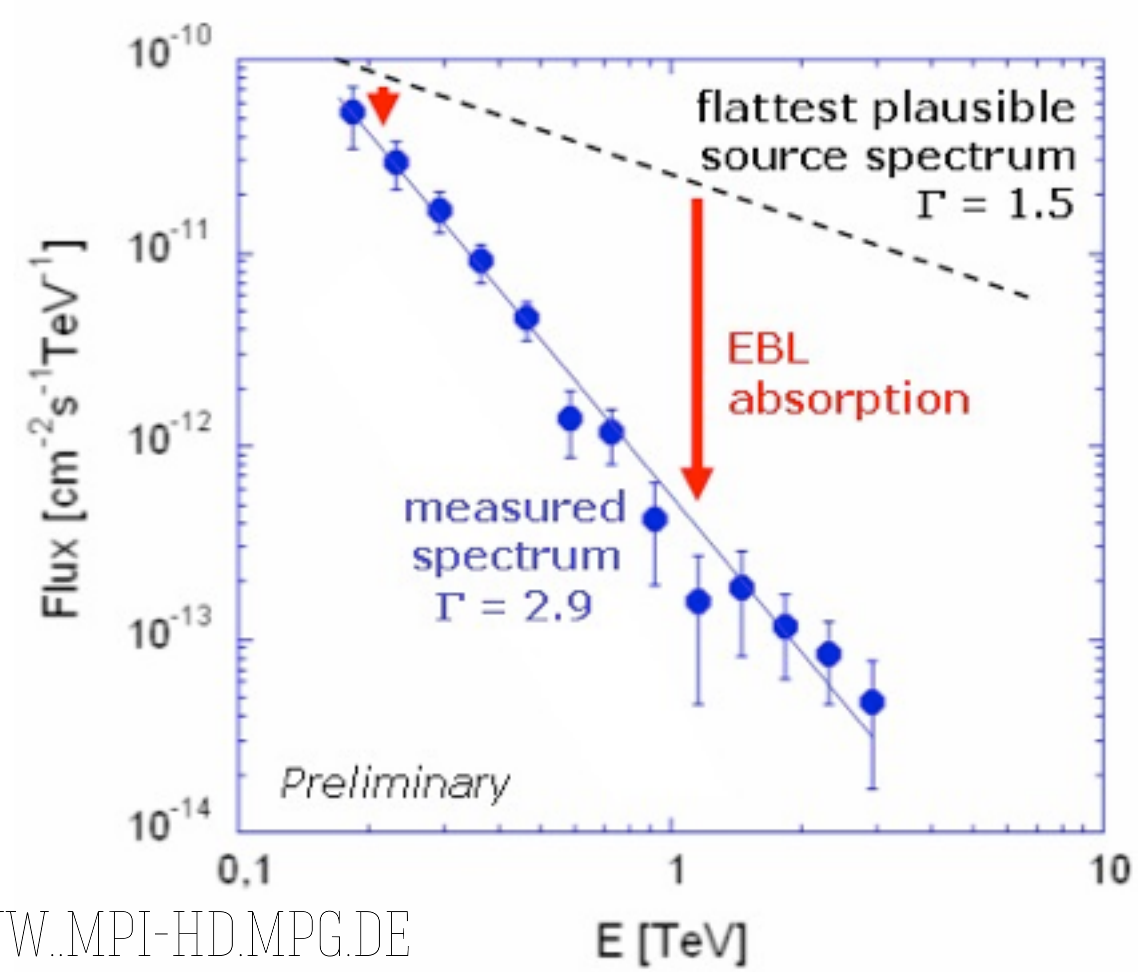

WWW.MPI-HD.MPG.DE

2006 observations of 1ES 1101-232 (z=0.186) by HESS ruled out many EBL models

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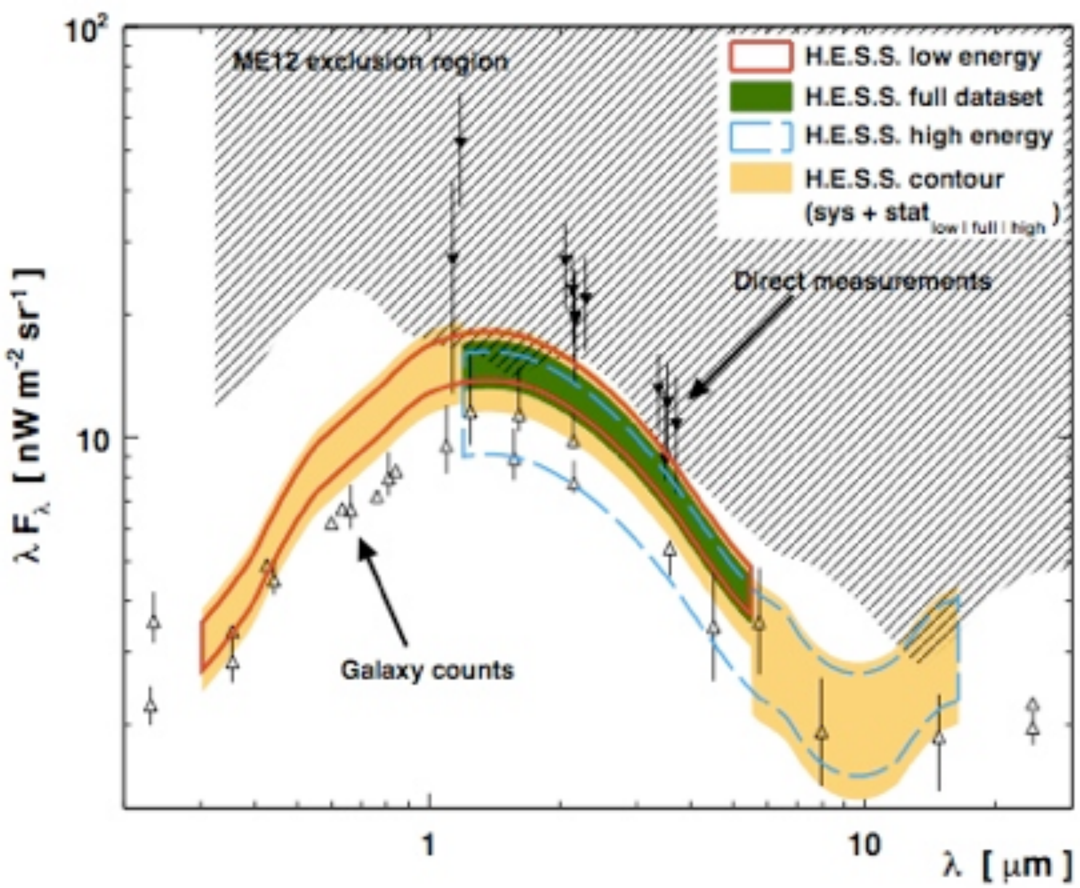

More recently (2012) HESS data on seven blazars were used to search for the absorption signature of the EBL - it was detected at 9 sigma - results are only slightly above the lower limits calculated by summing galaxies visible in sky surveys ASTRO-PH/1212.3409

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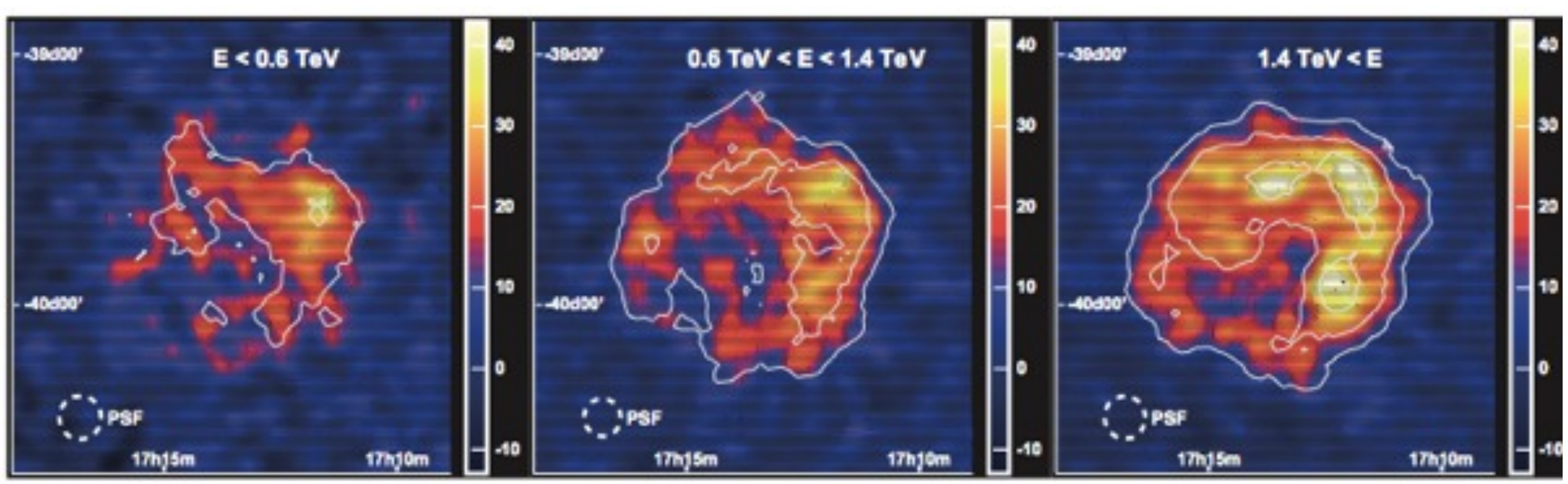
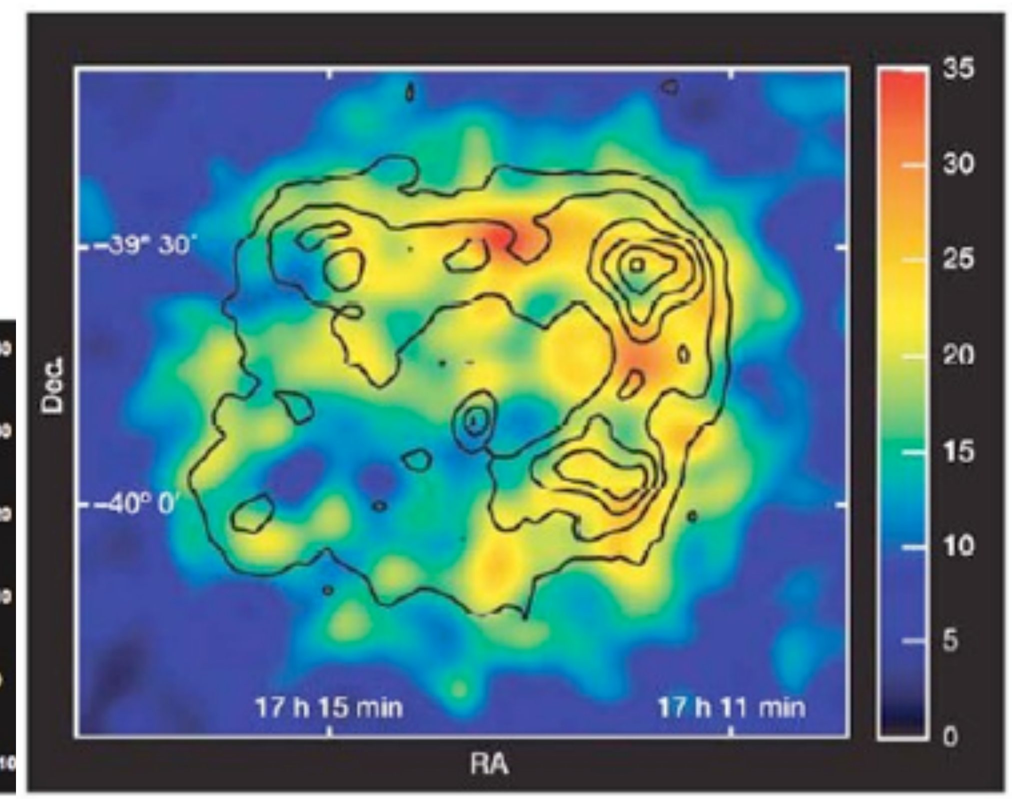
2006: Morphological studies of RXJ1713.7-3946 & HESS J1825-137

- spectra were derived for different energy bands

WWW.MPI-HD.MPG.DE

AHARONIAN ET AL. (2006), A&A, 449, 223





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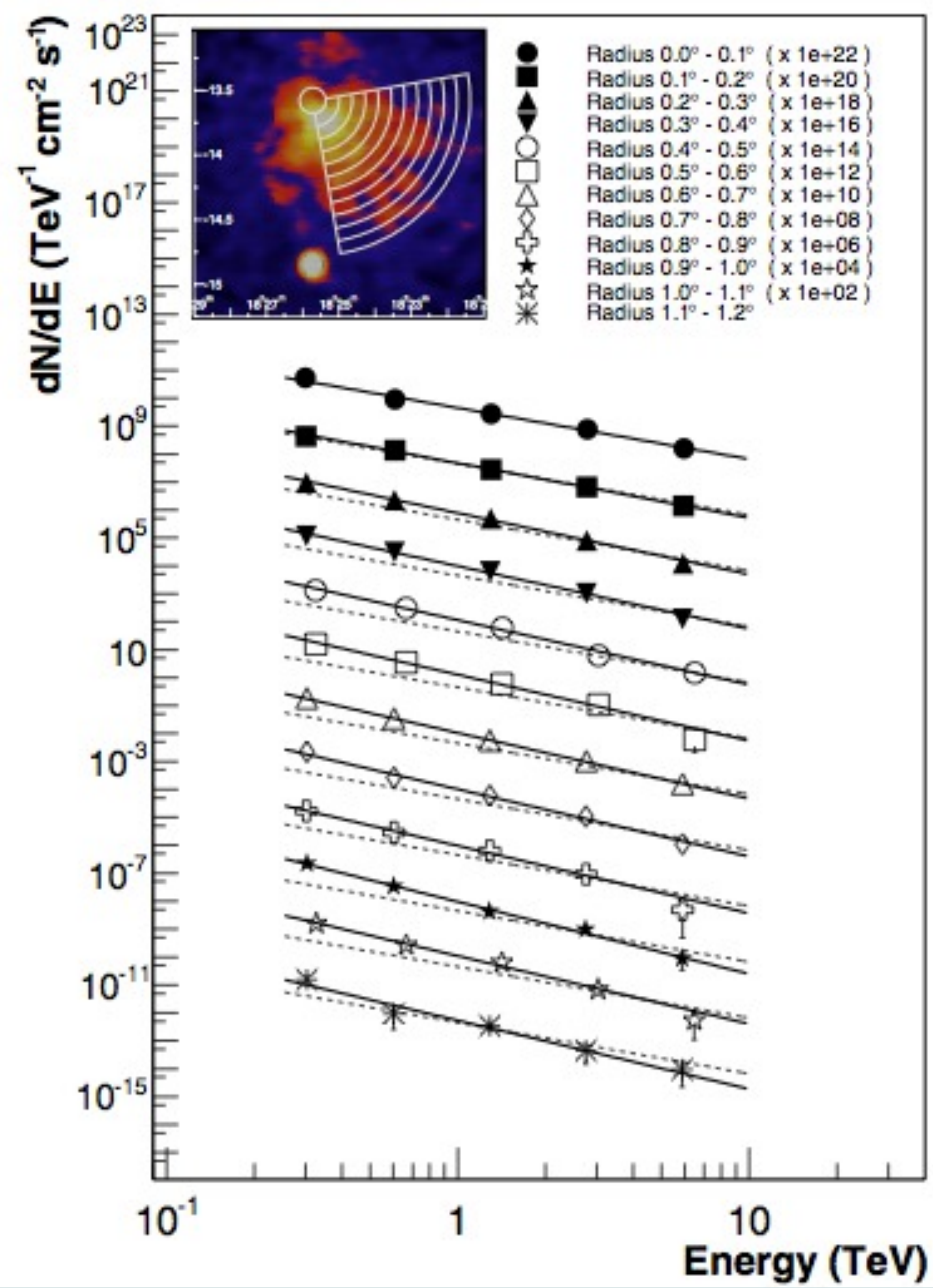
- spectra were derived for different energy bands

energy dependant morphology at TeV energies



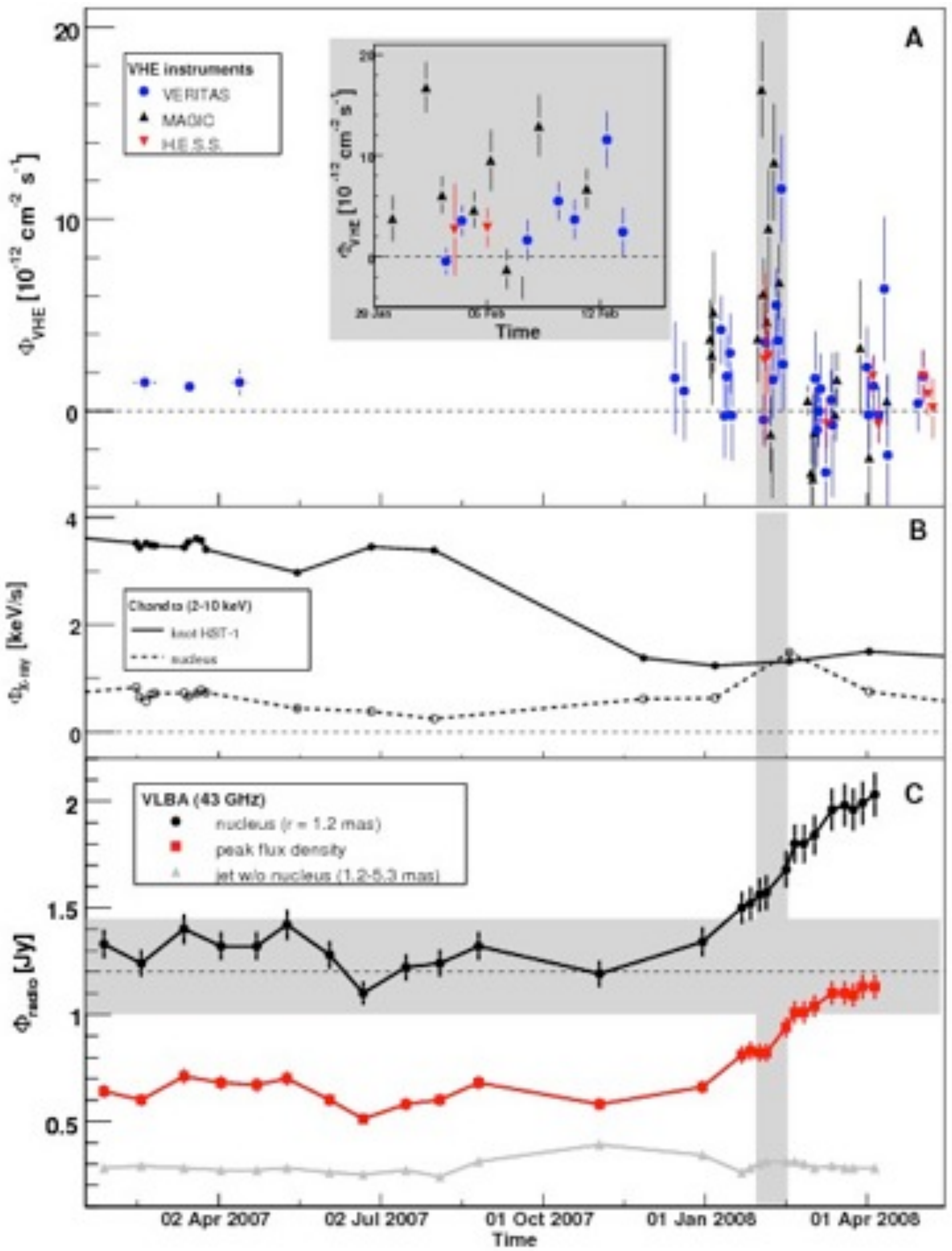
AHARONIAN ET AL. (2006), A&A, 460, 365

Third Generation Telescopes

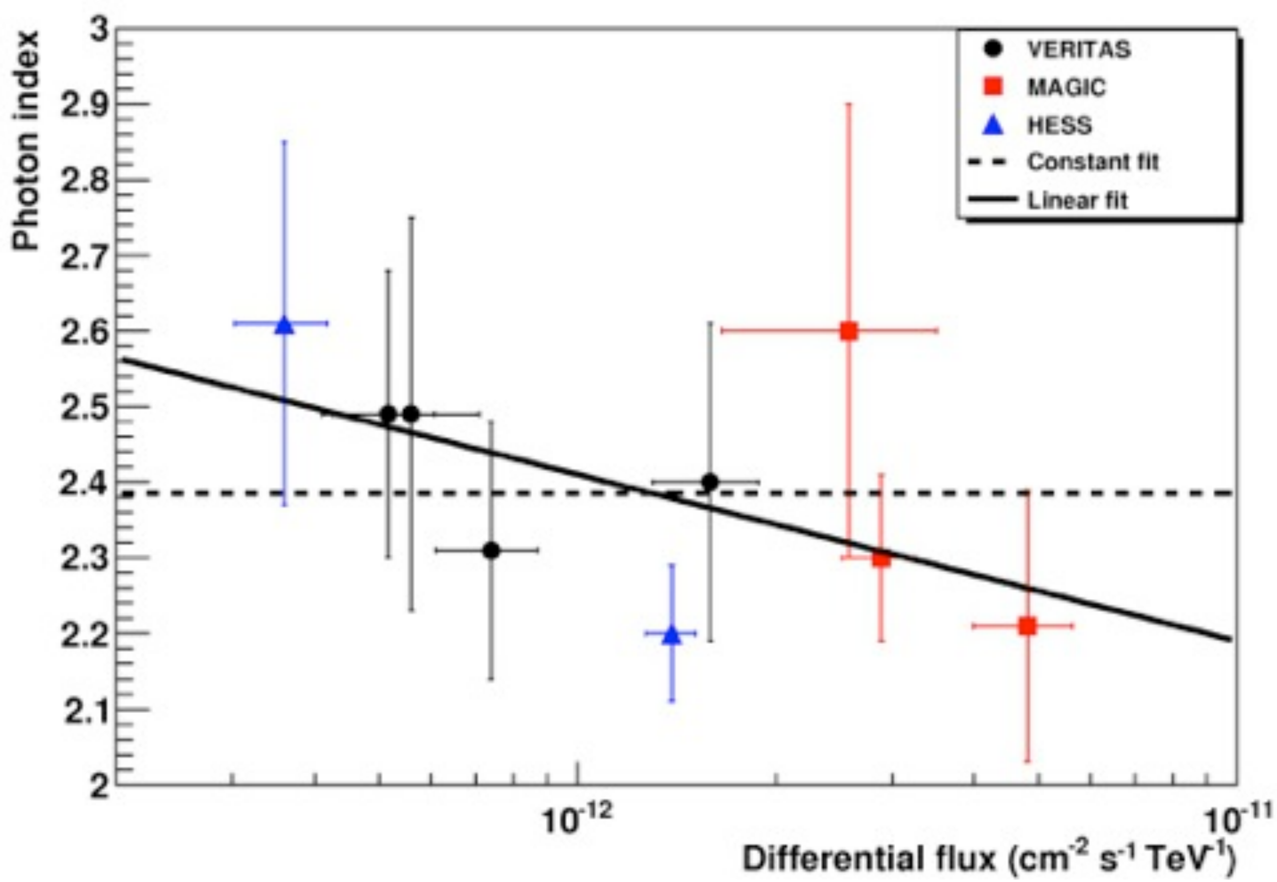
Some highlights of third generation instruments:

2006–: M87 and LSI +61 303 ... Multiwavelength studies with MULTIPLE TeV instruments

- data from multiple TeV instruments helps study jets in M87 and lightcurve of binary



Acciari et al. (2009), Science, 325, 444



Acciari et al. (2010), ApJ, 716, 819

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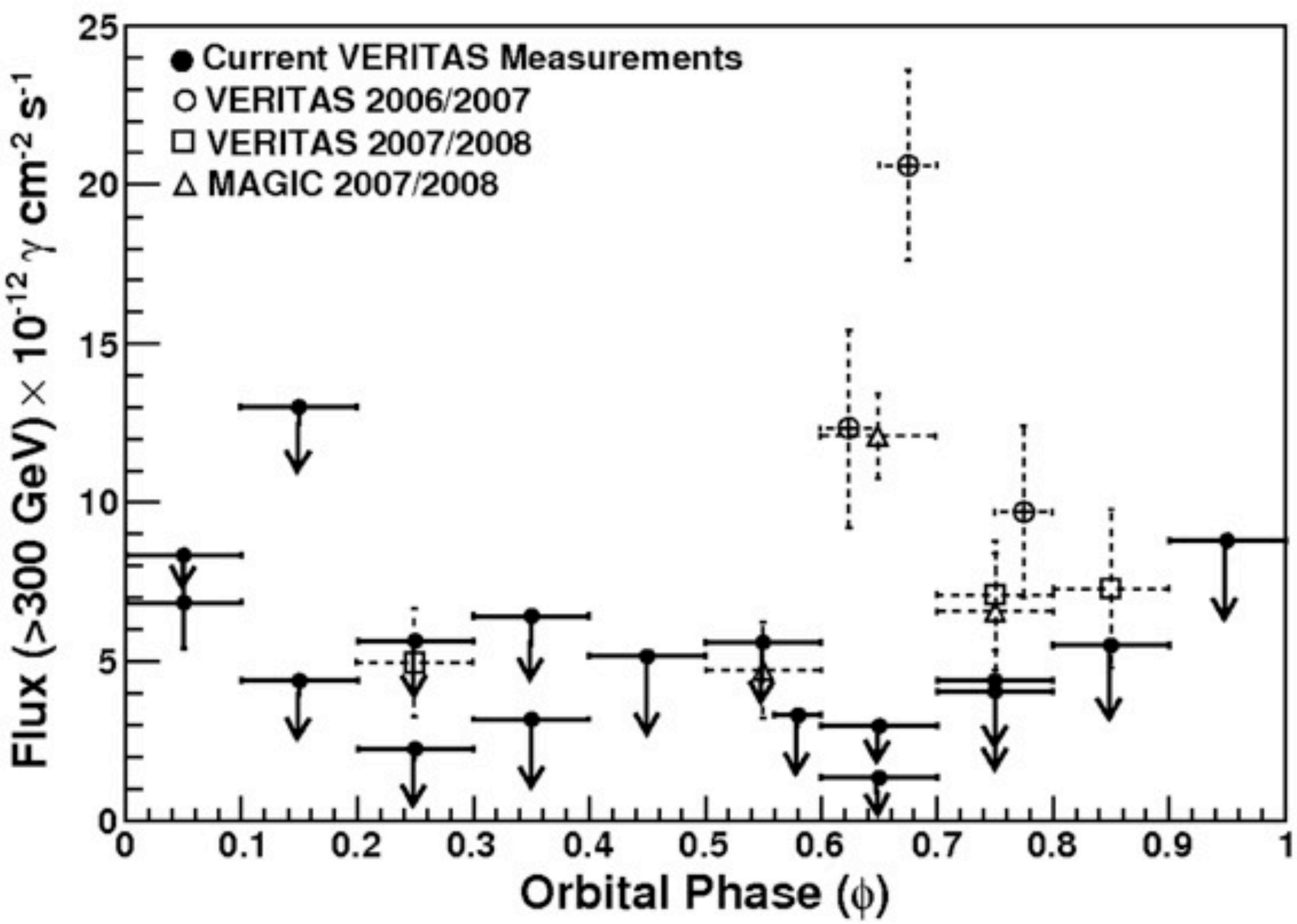

Acciari et al. (2011), ApJ, 738, 3

Third Generation Telescopes

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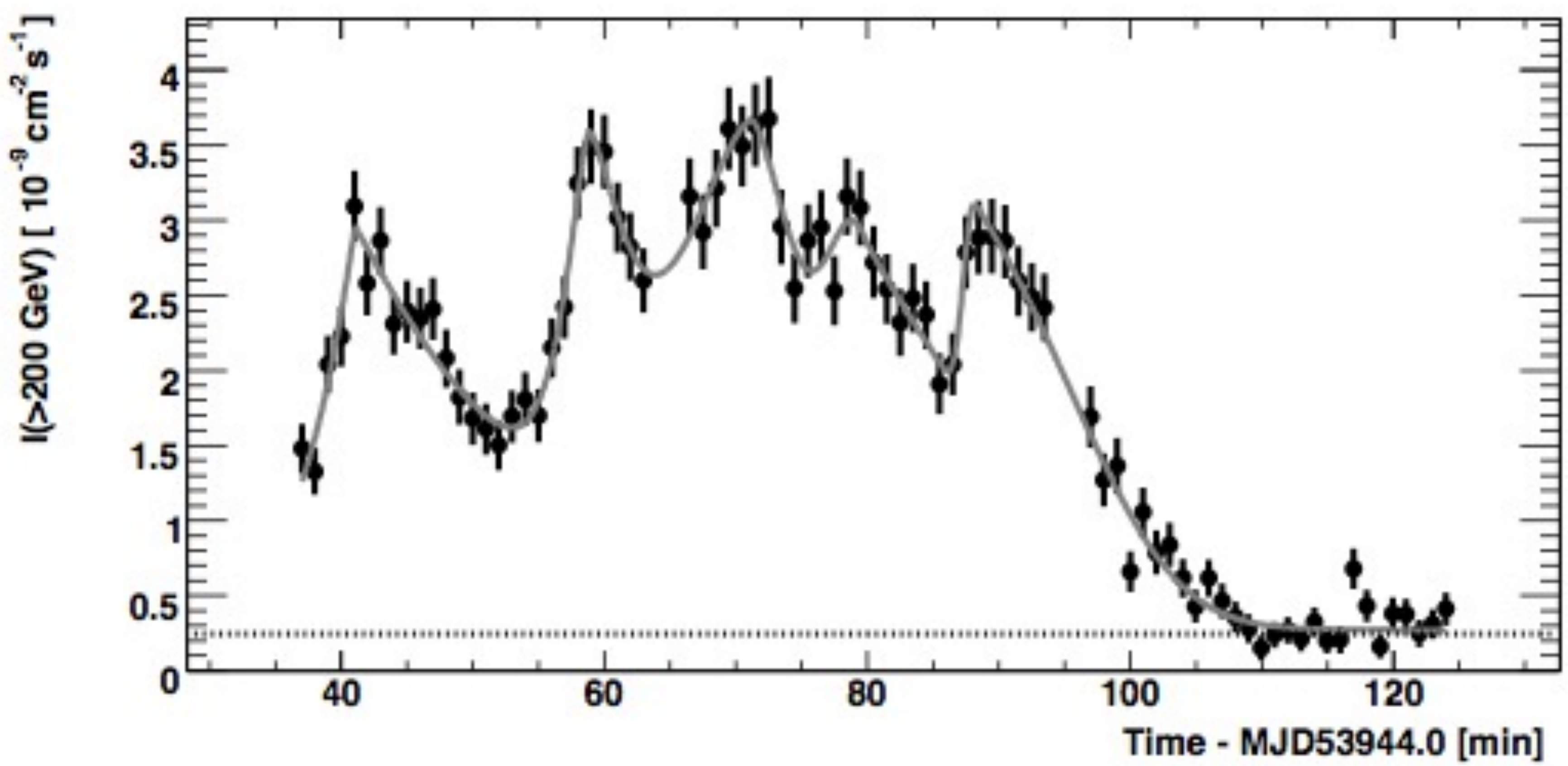
- data from multiple TeV instruments helps study jets in M87 and lightcurve of binary

2007: Extremely rapid flaring from blazar PKS 2155-514

- lightcurve was binned in one-minute bins!



Aharonian et al. (2007), ApJ, 730, L8

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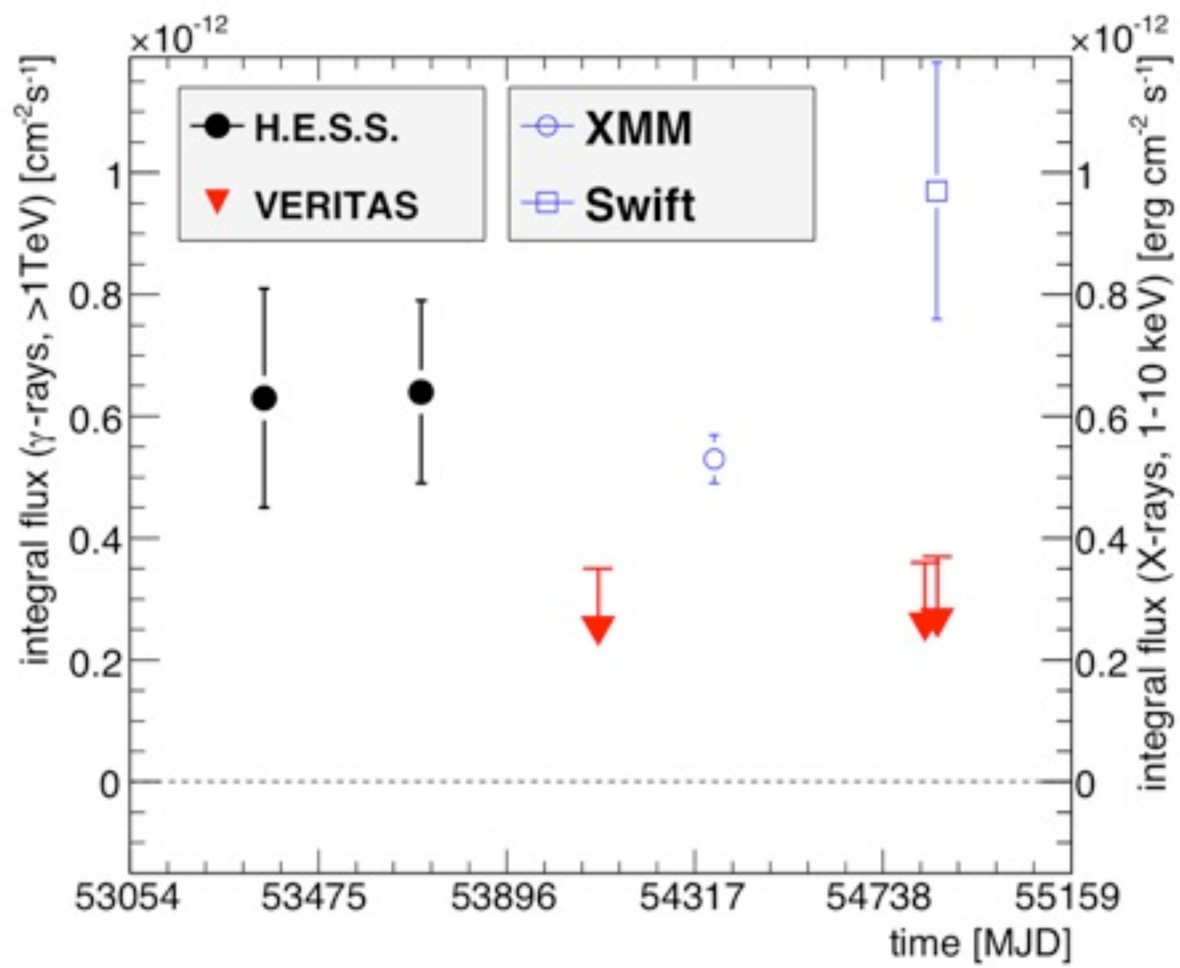
2007/11: Binary nature of HESS J0632+057

- VERITAS data provides first evidence that HESS source is a binary



ACCIARI ET AL. (2009), APJ, 698, L94

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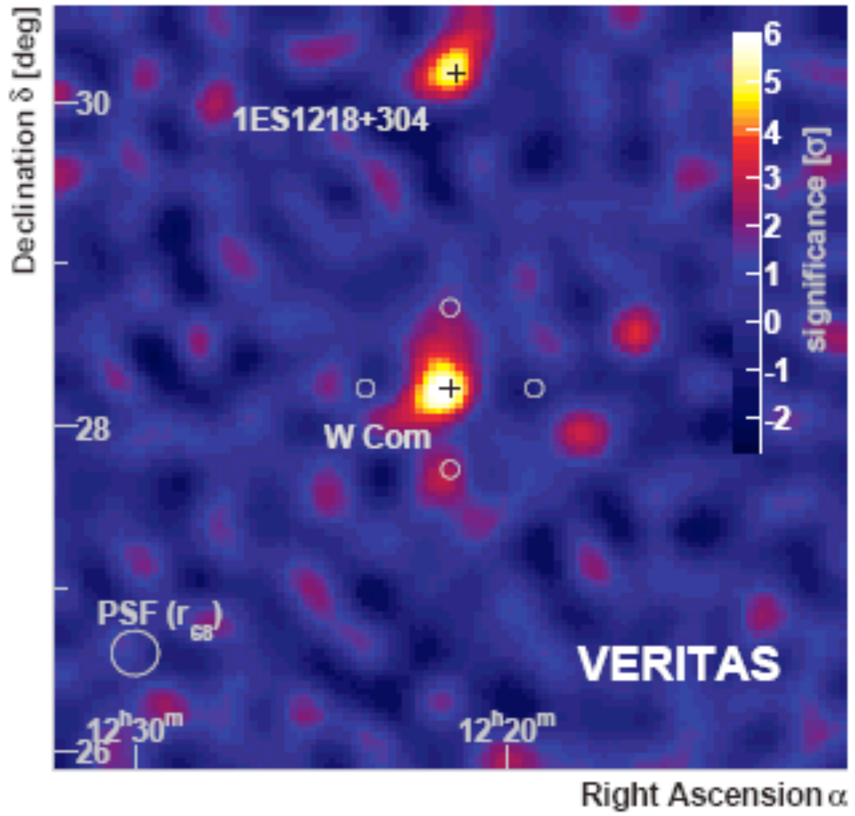
2007/11: Binary nature of HESS J0632+057

- VERITAS data provides first evidence that HESS source is a binary

2008: Two extragalactic sources in same field of view

- two AGN are detected in one field of view - there are a LOT of TeV sources now!

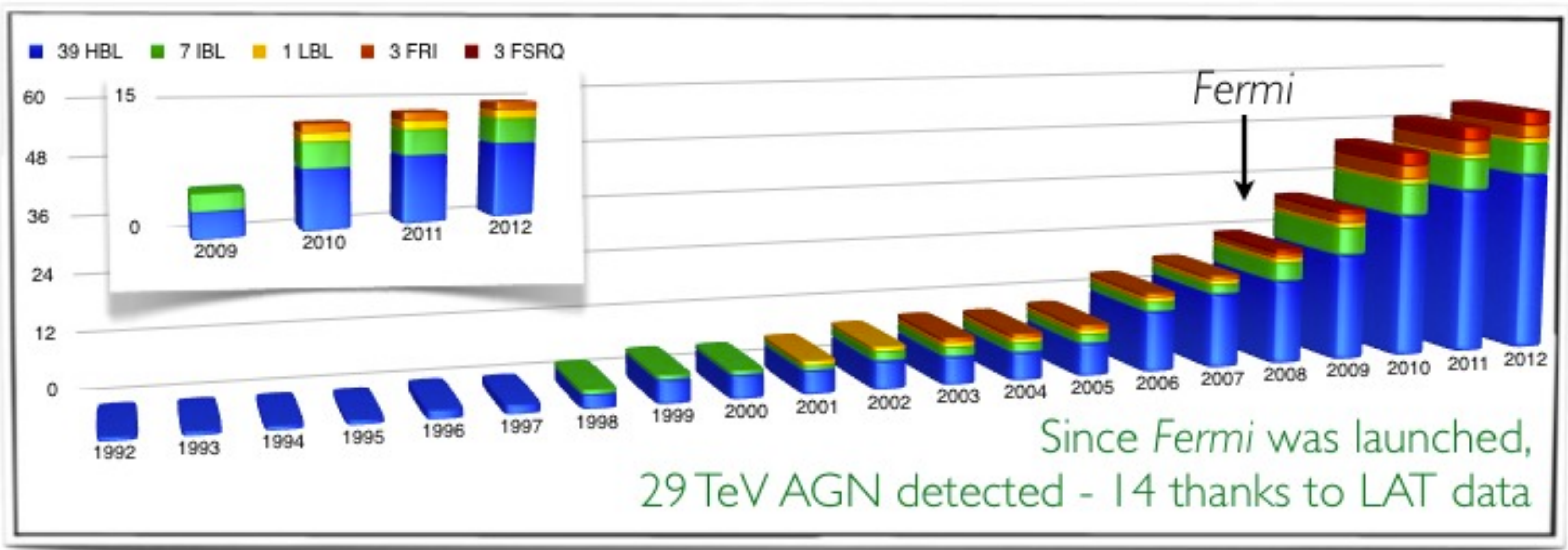


VERITAS COLLABORATION

Third Generation Telescopes

Some highlights of third generation instruments:

2008--: Fermi guides TeV instruments to find many new sources – mostly blazars so far



Third Generation Telescopes

The growth in sources detected by the third generation telescopes was such that it was no longer possible to keep track of the state of the field without the help of some sort of one-stop "clearing house"

with this in mind, TeVCat was created in 2008

Scott Wakely (U.Chicago) and DH

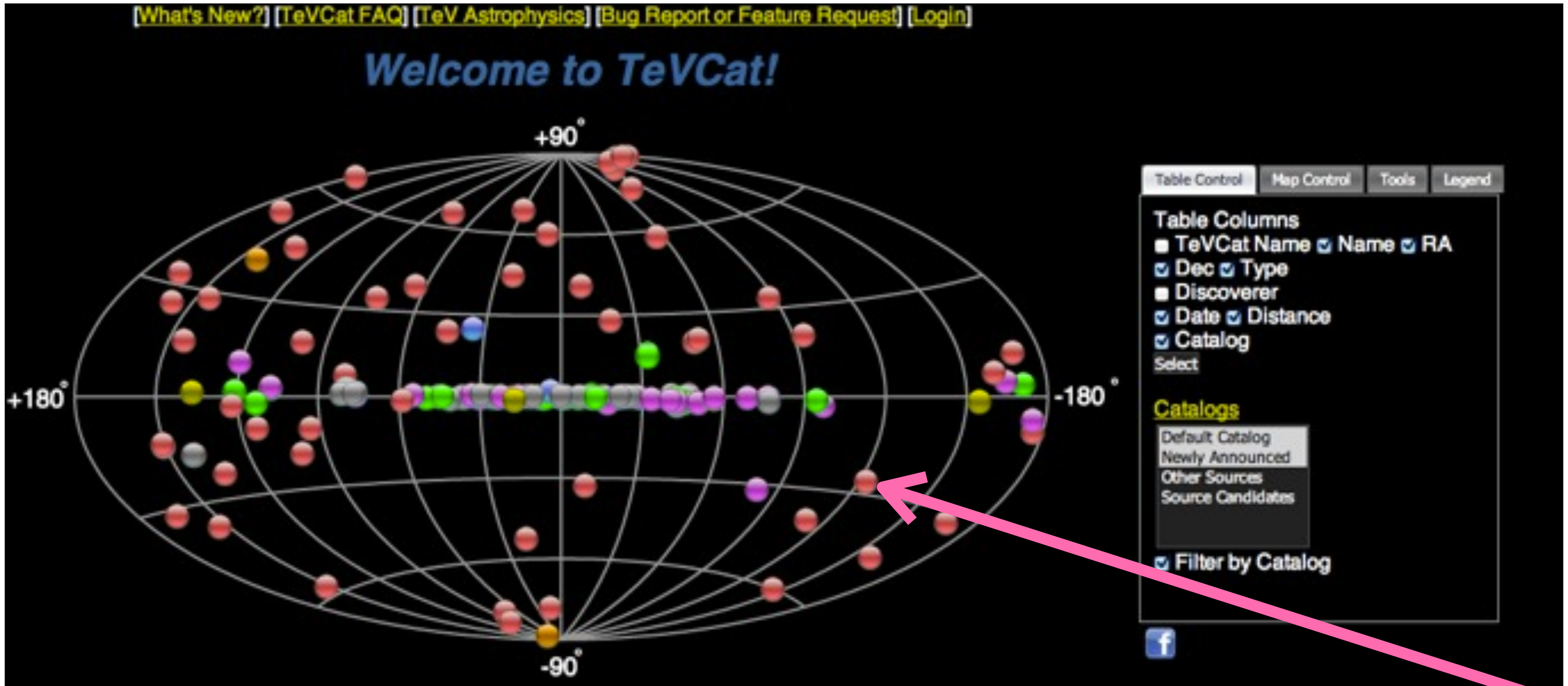
http://tecvat.uchicago.edu

or

http://tevcat.in2p3.fr

TeVCat
- status of the TeV sky
11/11

TeVCat - status of the TeV sky



Select All Unselect All Plot Selected Plot All Plot UnSelected Filter Selected Clear Filters

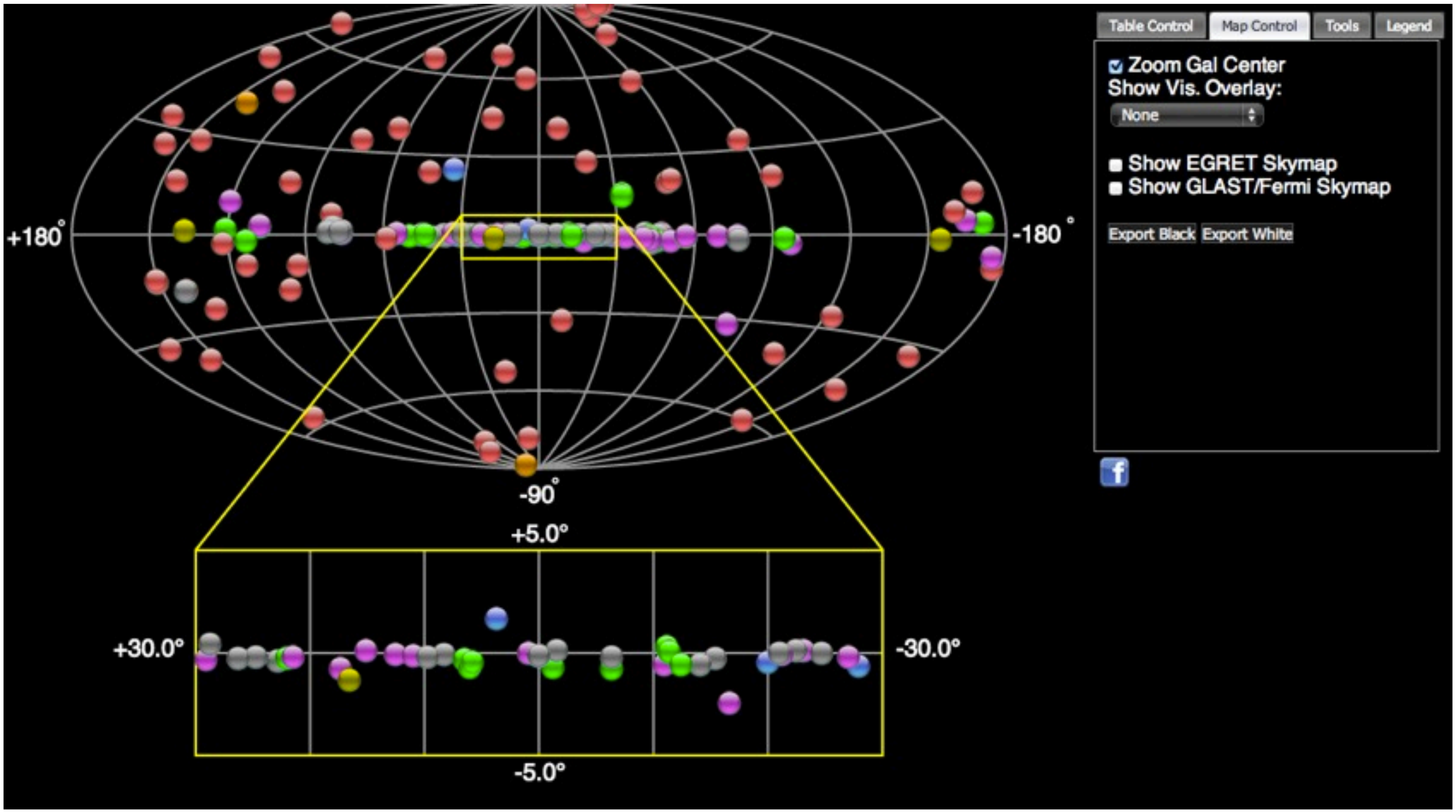
Reg Exp: OK

Name	RA	Dec	Type	Date	Dist	Catalog
CTA 1	00 06 26	+72 59 01.0	PWN	2011.10	1.4 kpc	Default Catalog
SHBL J001355.9-185406	00 13 52.0	-18 53 29	HBL	2010.11	z = 0.095	Default Catalog
Tycho	00 25 27	[illegible]	Shell	2010.05	3.5 kpc	Default Catalog
KUV 00311-1938	00 33 34.2	-19 21 33	HBL	2012.07		Newly Announced
1ES 0033+595	00 35 52.63	+59 50 04.56	HBL	2011.10		Newly Announced
NGC 253	00 47 34.3	-25 17 22.6	Starburst	2009.07	2500 kpc	Default Catalog
RGB J0136+391	01 36 32.5	+39 06 00	HBL	2012.07		Newly Announced
RGB J0152+017	01 52 33.5	+01 46 40.3	HBL	2008.02	z = 0.08	Default Catalog
3C66A	02 22 41.6	+43 02 35.5	IBL	1998.03	z = 0.41	Default Catalog
MAGIC J0223+403	02 23 12	+43 00 42	UNID	2009.02		Default Catalog
1ES 0229+200	02 32 53.2	+20 16 21	HBL	2006.12	z = 0.14	Default Catalog
LSI +61 303	02 40 34	+61 15 25	XRB	2006.06	2 kpc	Default Catalog
PKS 0301-243	03 03 26.5	-24 07 11	HBL	2012.07		Newly Announced
IC 310	03 16 43.0	+41 19 29	HBL	2010.03	z = 0.0189	Newly Announced
RBS 0413	03 19 47	+18 45 42	HBL	2009.10	z = 0.19	Default Catalog
NGC 1275	03 19 48.1	+41 30 42	FRI	2010.10	z = 0.017559	Default Catalog
1ES 0347-121	03 49 23.0	-11 58 38	HBL	2007.08	z = 0.188	Default Catalog
1ES 0414+009	04 16 52.96	+01 05 20.4	HBL	2009.11	z = 0.287	Default Catalog
PKS 0447-439	04 49 28.2	-43 50 12	HBL	2009.12		Default Catalog
1ES 0502+675	05 07 56.2	+67 37 24	HBL	2009.11	z = 0.341	Newly Announced
VER J0521+211	05 21 55	+21 11 24	IBL	2009.10		Newly Announced
Crab	05 34 31.1	+22 00 52	PWN	1989.07	2 kpc	Default Catalog
N 157B	05 37 44	-69 09 57	PWN	2012.01	48 kpc	Default Catalog
PKS 0548-322	05 50 38.4	-32 16 12.9	HBL	2007.07	z = 0.069	Default Catalog
IC443	06 16 51	+22 30 11	Shell	2007.05	1.5 kpc	Default Catalog
Geminga	06 32 28	+17 22 00	PWN	2009.04	0.169 kpc	Default Catalog
HESS J0632+057	06 32 58.3	+05 48 20	Gamma BIN	2007.07	1.6 kpc	Default Catalog
RX J0648.7+1516	06 48 45.6	+15 16 12	HBL	2010.03	z = 0.179	Default Catalog
1ES 0647+250	06 50 46.5	+25 03 00	HBL	2011.09	z = 0.45	Newly Announced
RGB J0710+591	07 10 26.4	59 09 00	HBL	2009.02	z = 0.125	Default Catalog
S5 0716+714	07 21 53.4	+71 20 36	IBL	2008.04	z = 0.31	Default Catalog

by clicking on map or on table, can proceed to further information about each source

TeVCat - status of the TeV sky

Map Control ... zoom galactic centre, show overlays ...



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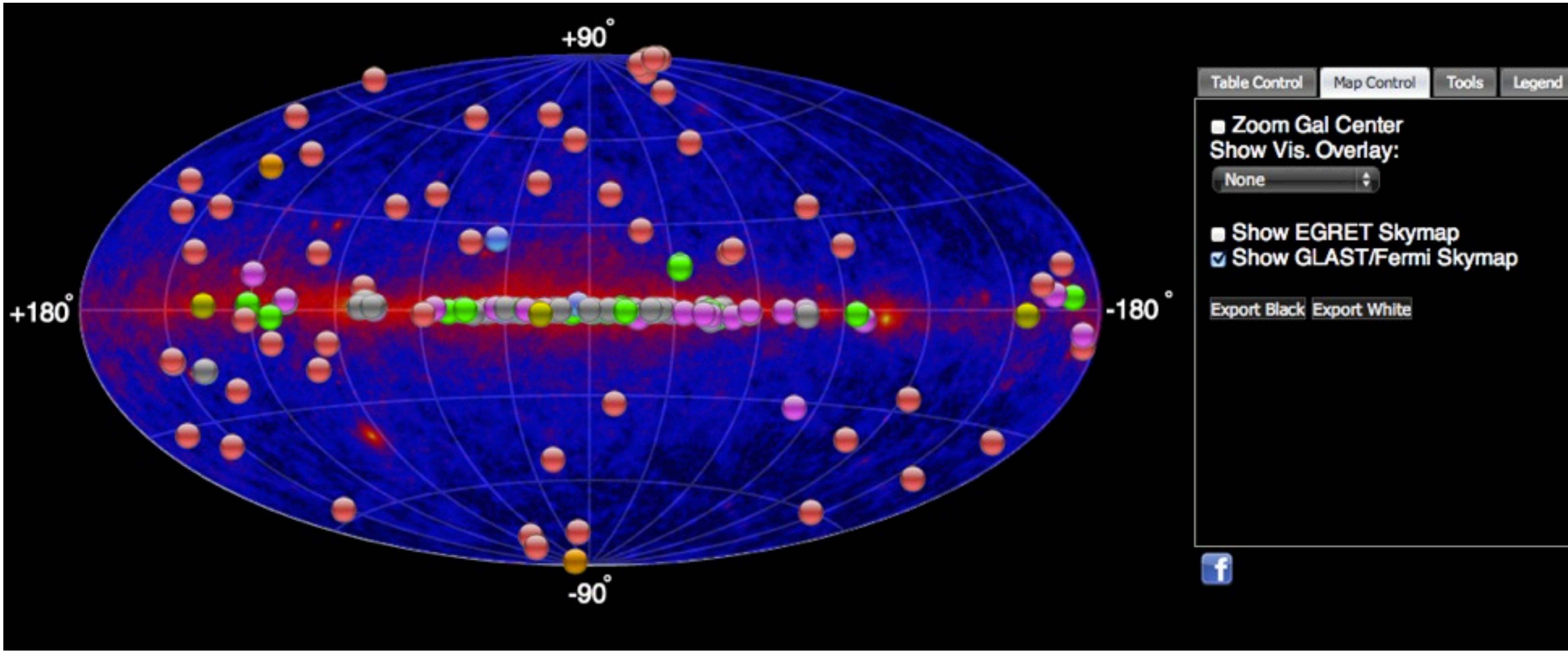
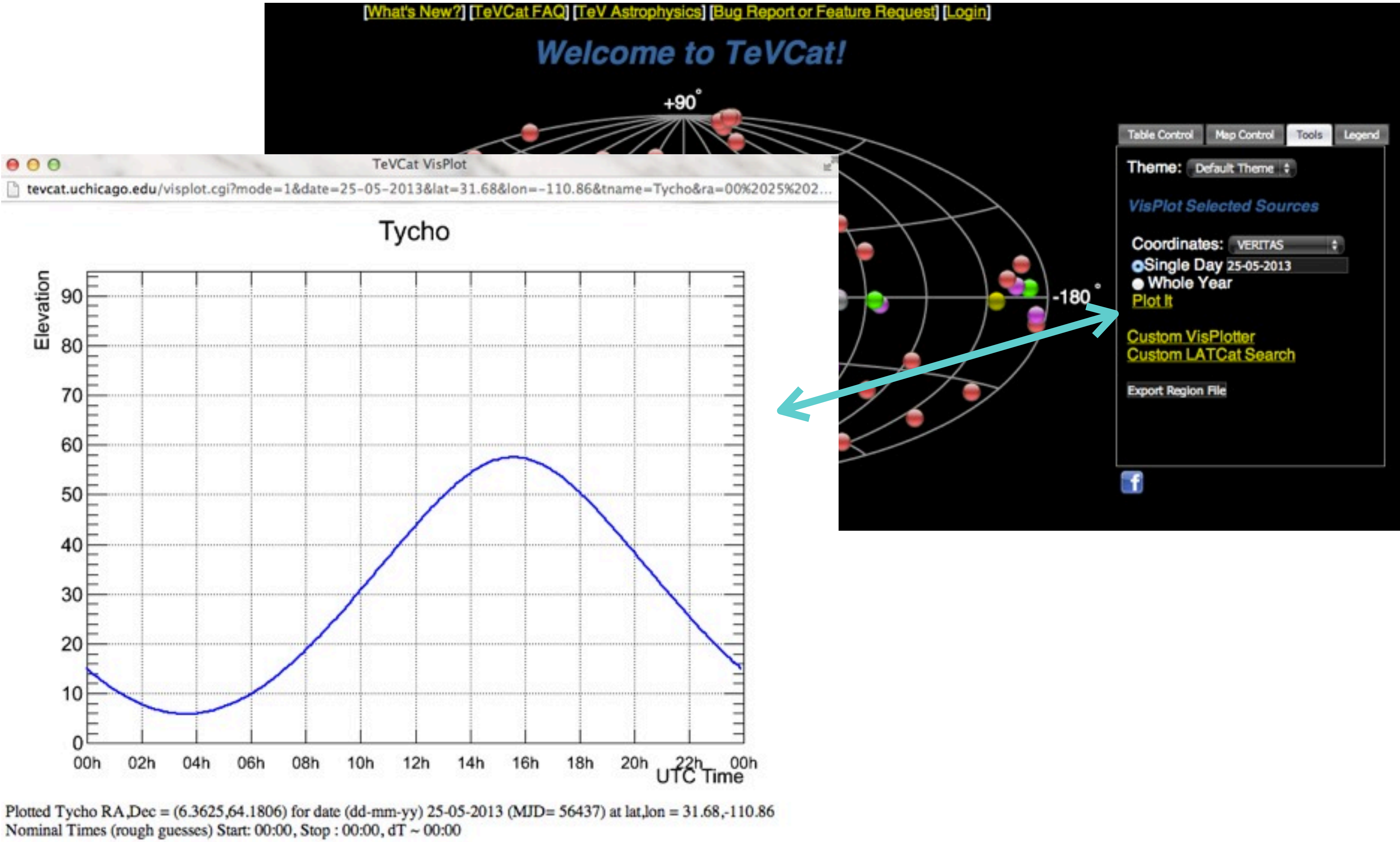


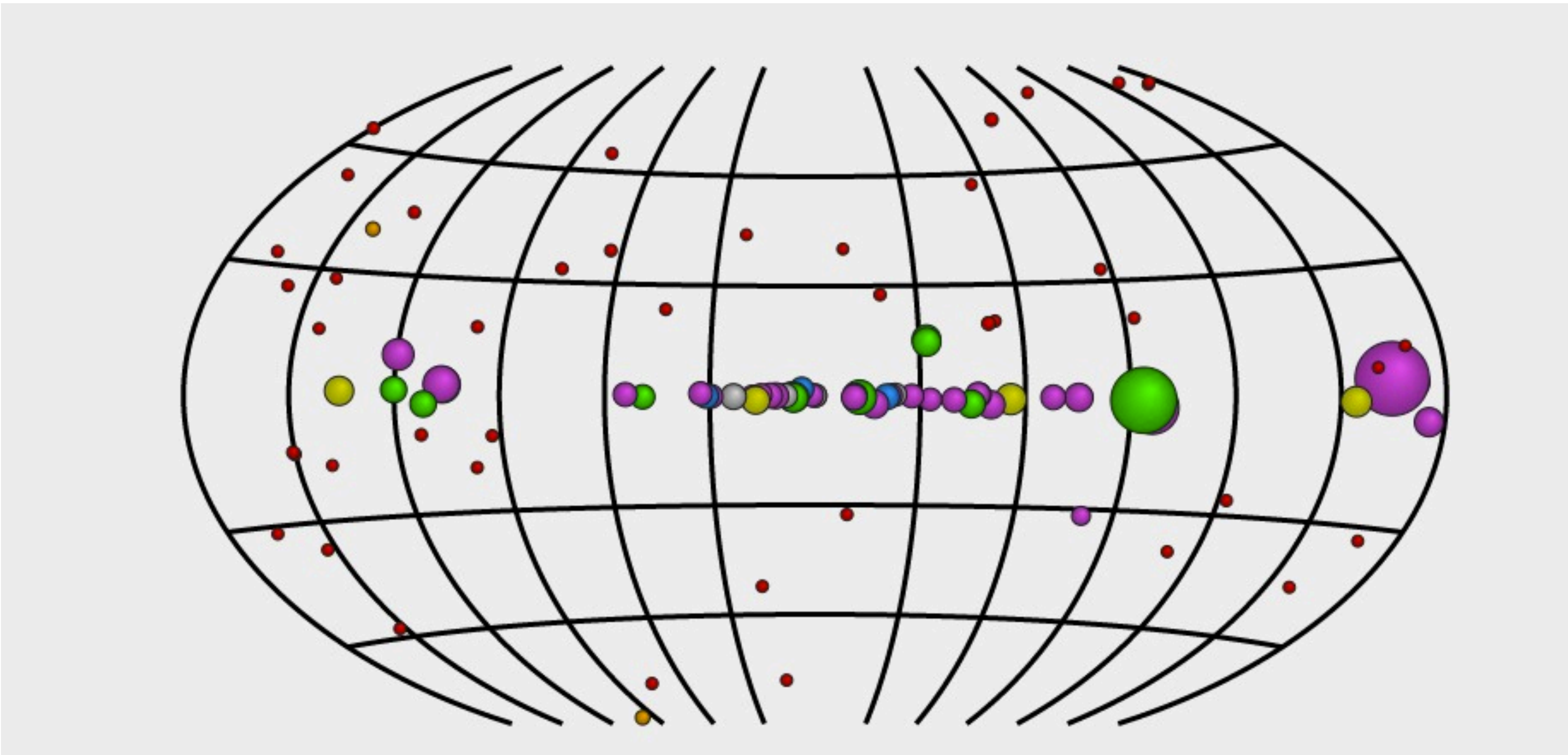
TeVCat - status of the TeV sky

Tools - plot the visibility of any source for any time for any location on Earth



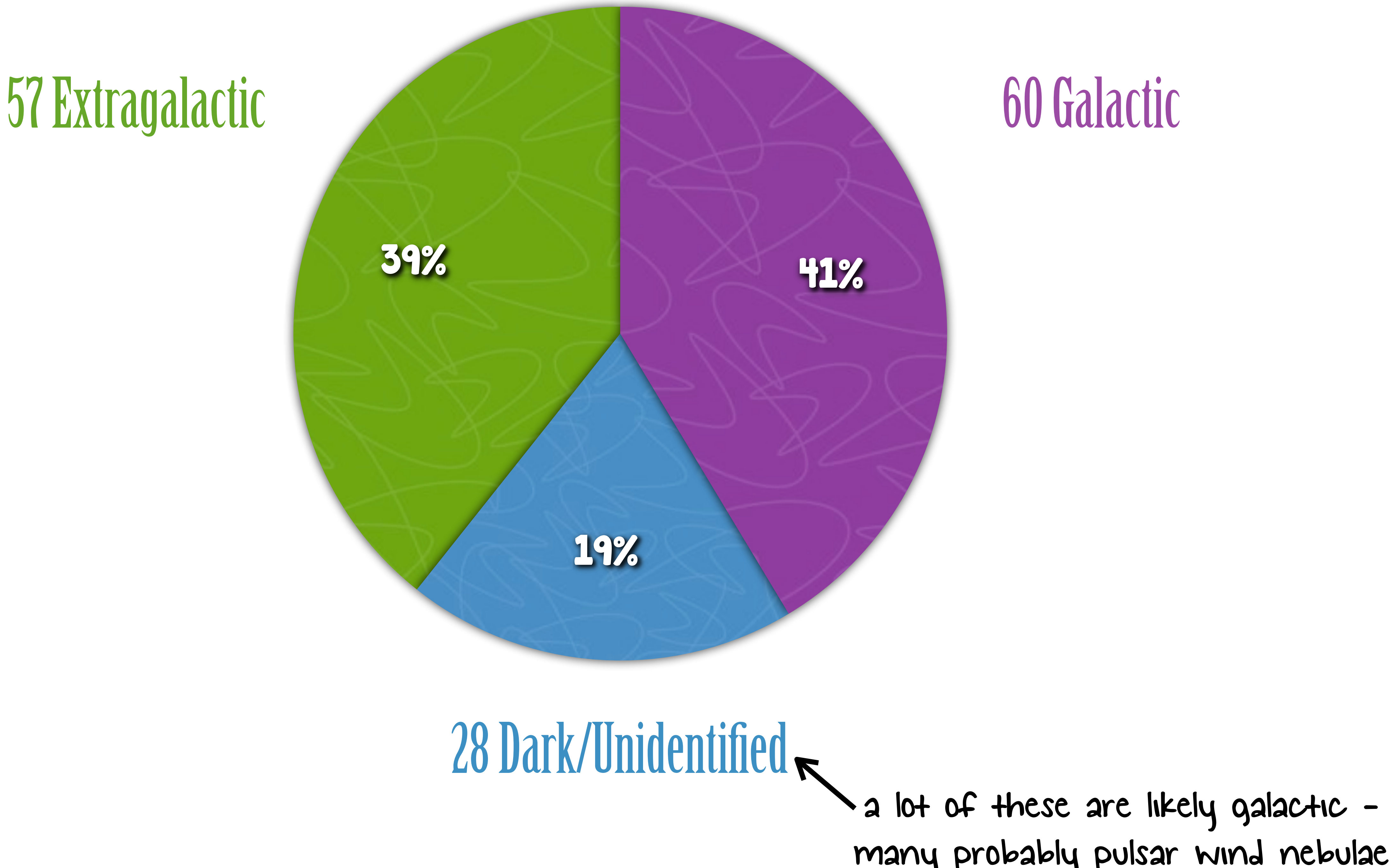
TeVCat - status of the TeV sky

New TeVCat coming soon ... lots more options



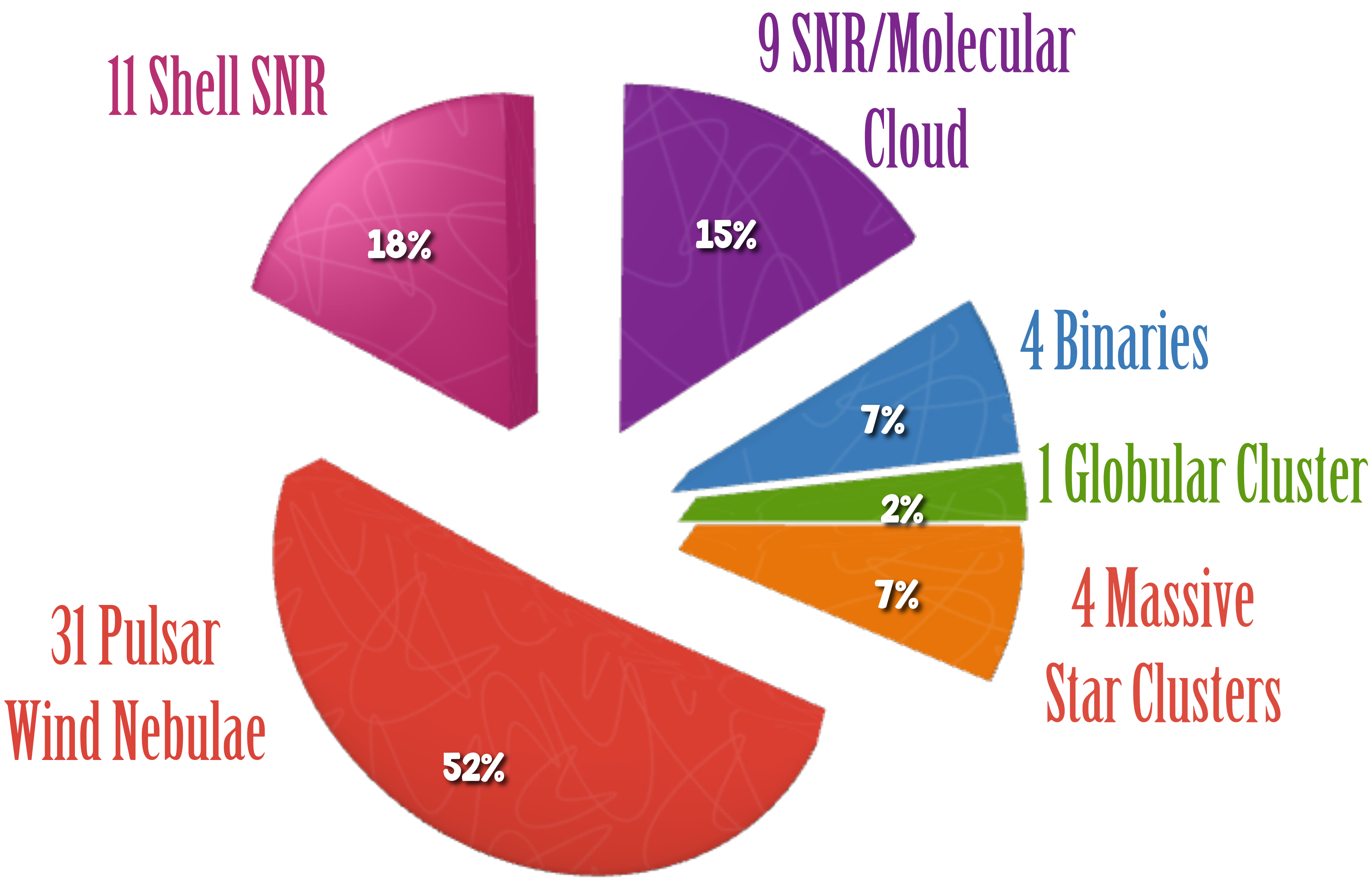
TeVCat - status of the TeV sky

As of writing this talk, there are 145 sources in TeVCat



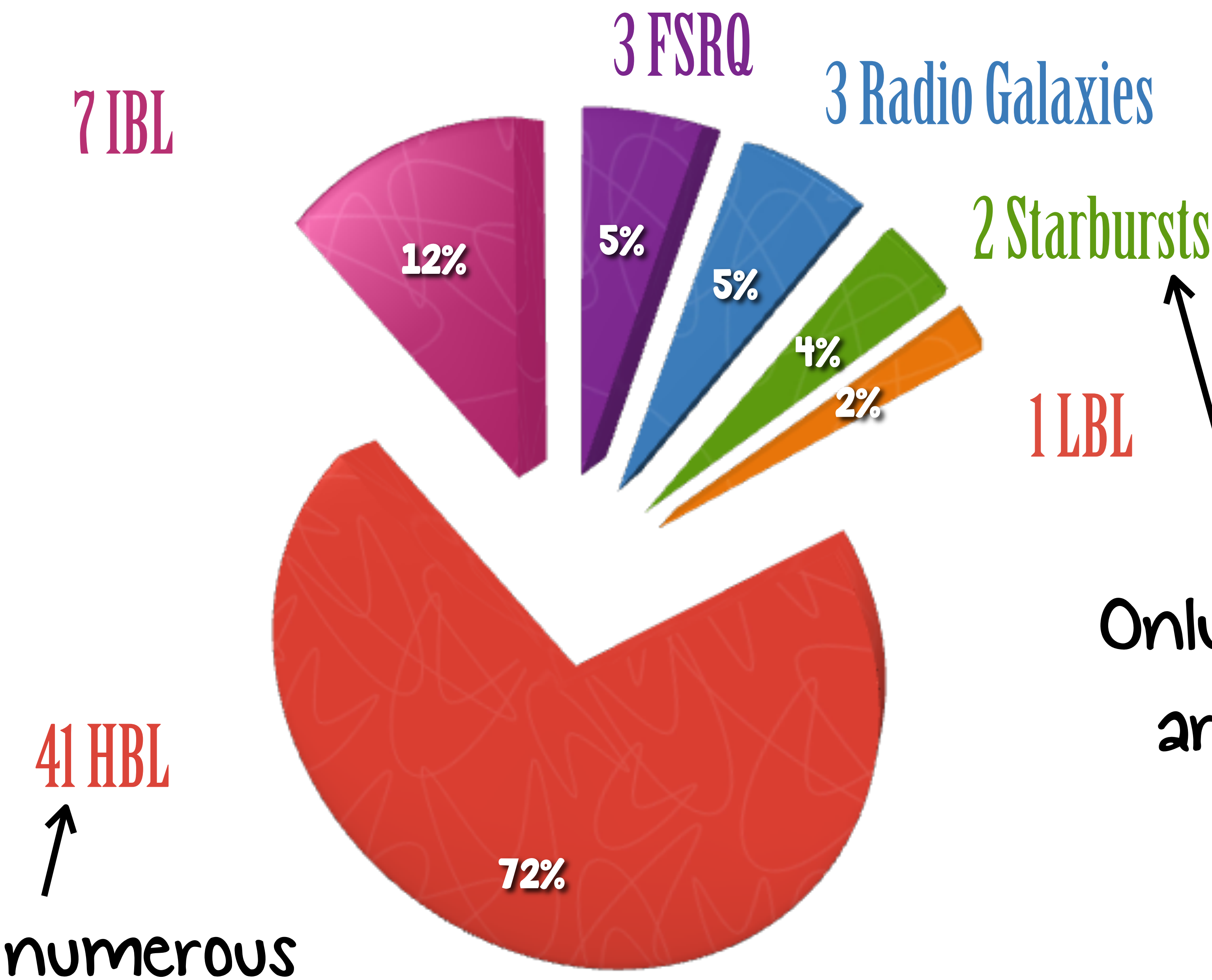
TeVCat - status of the TeV sky

As of writing this talk, there are 145 sources in TeVCat - 60 Galactic



TeVCat - status of the TeV sky

As of writing this talk, there are 145 sources in TeVCat - 57 Extragalactic

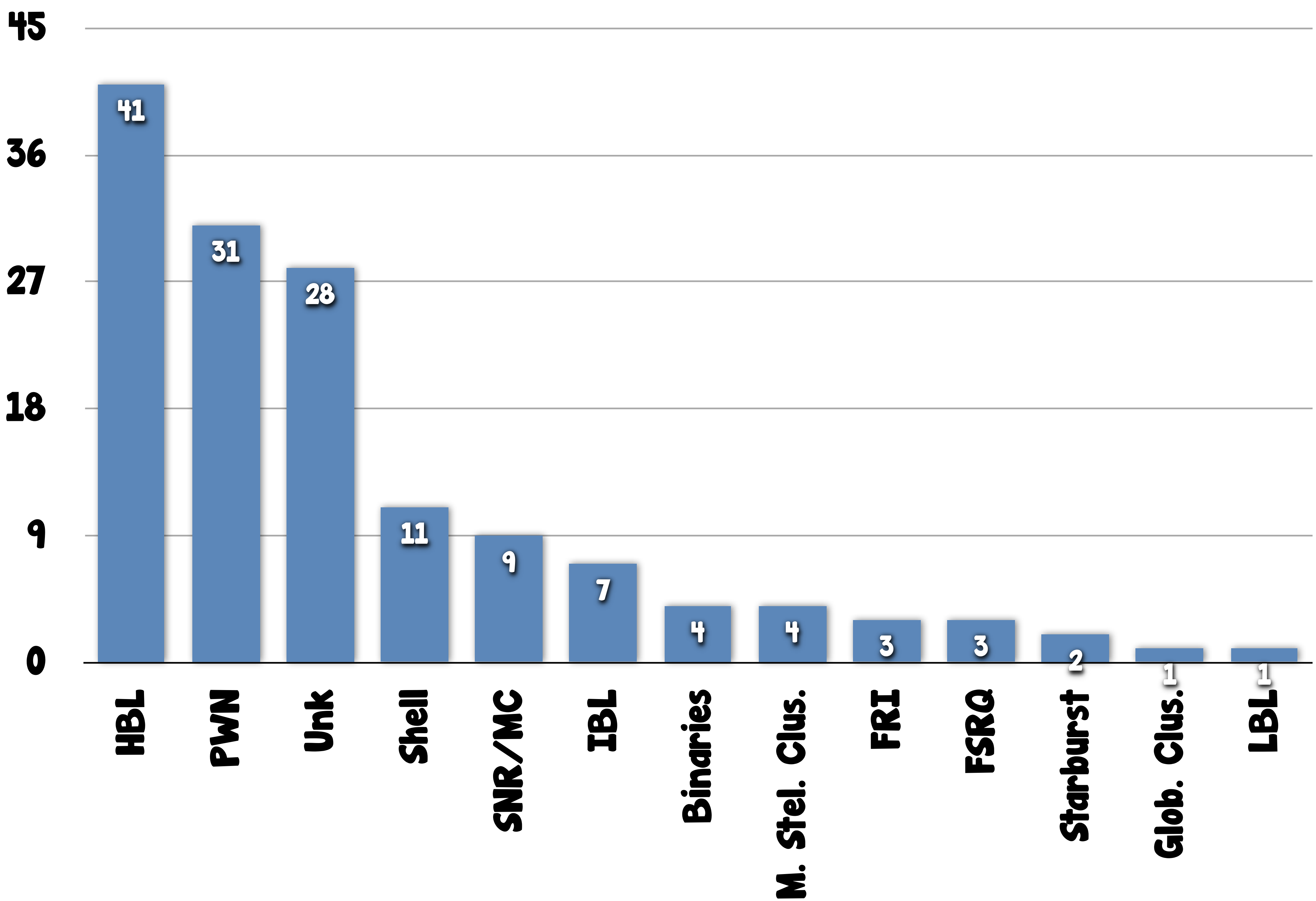


Only two sources are not AGN!

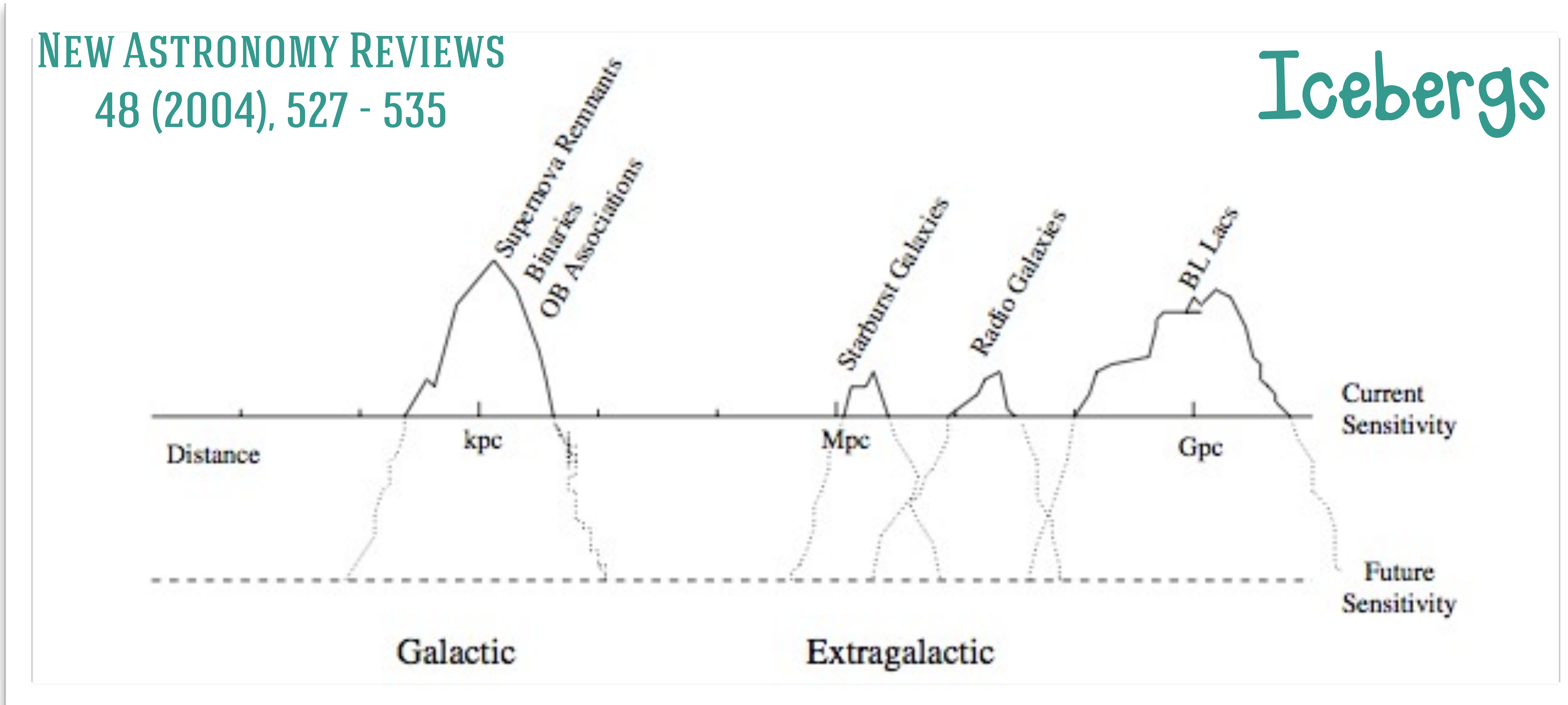
Most numerous source class in TeV sky

TeVCat - status of the TeV sky

As of writing this talk, there are 145 sources in TeVCat



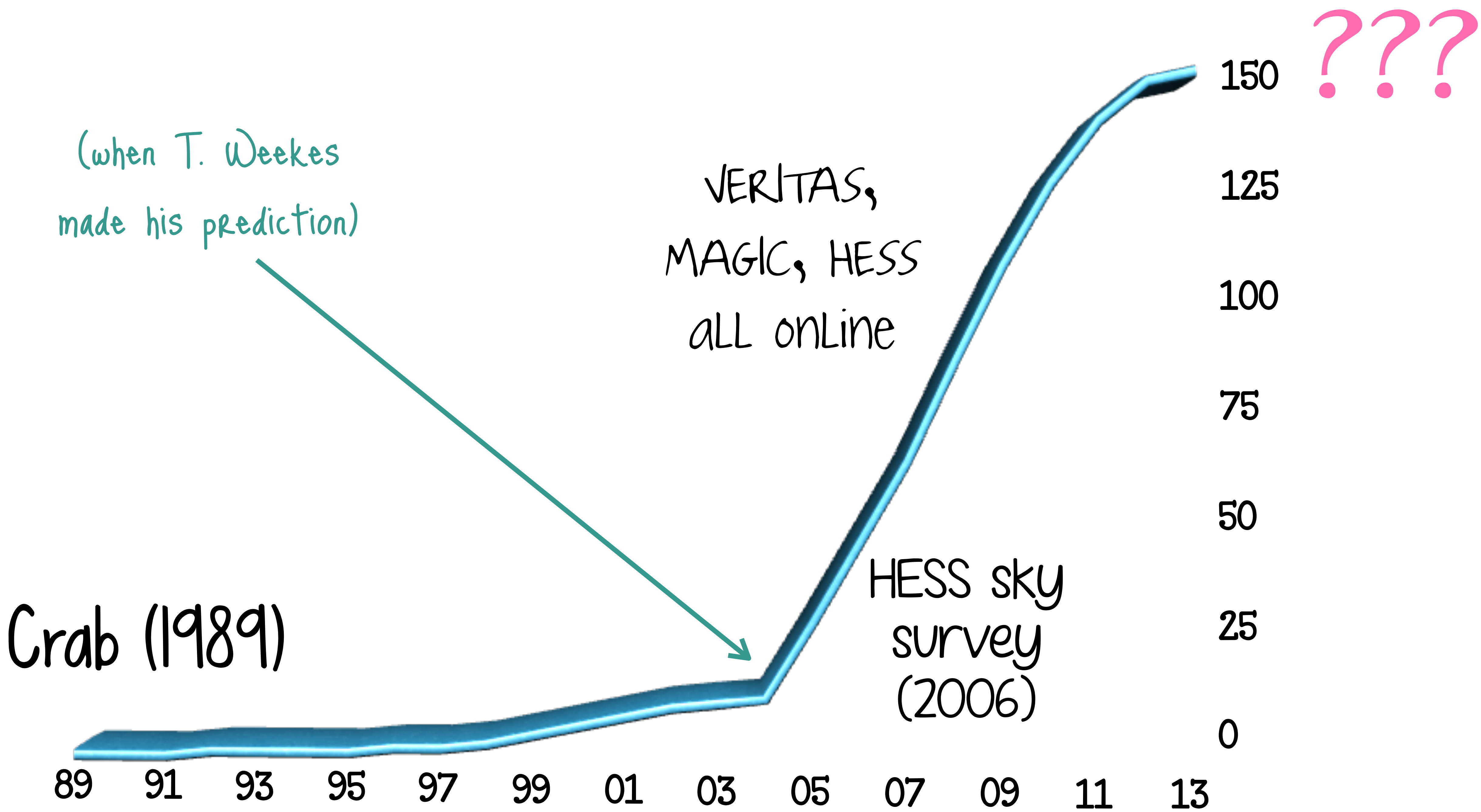
TeVCat - status of the TeV sky



A figure that T. Weekes created in 2004 to illustrate his view on the status of the field

TeVCat - status of the TeV sky

As of writing this talk, there are 145 sources in TeVCat



Thank you

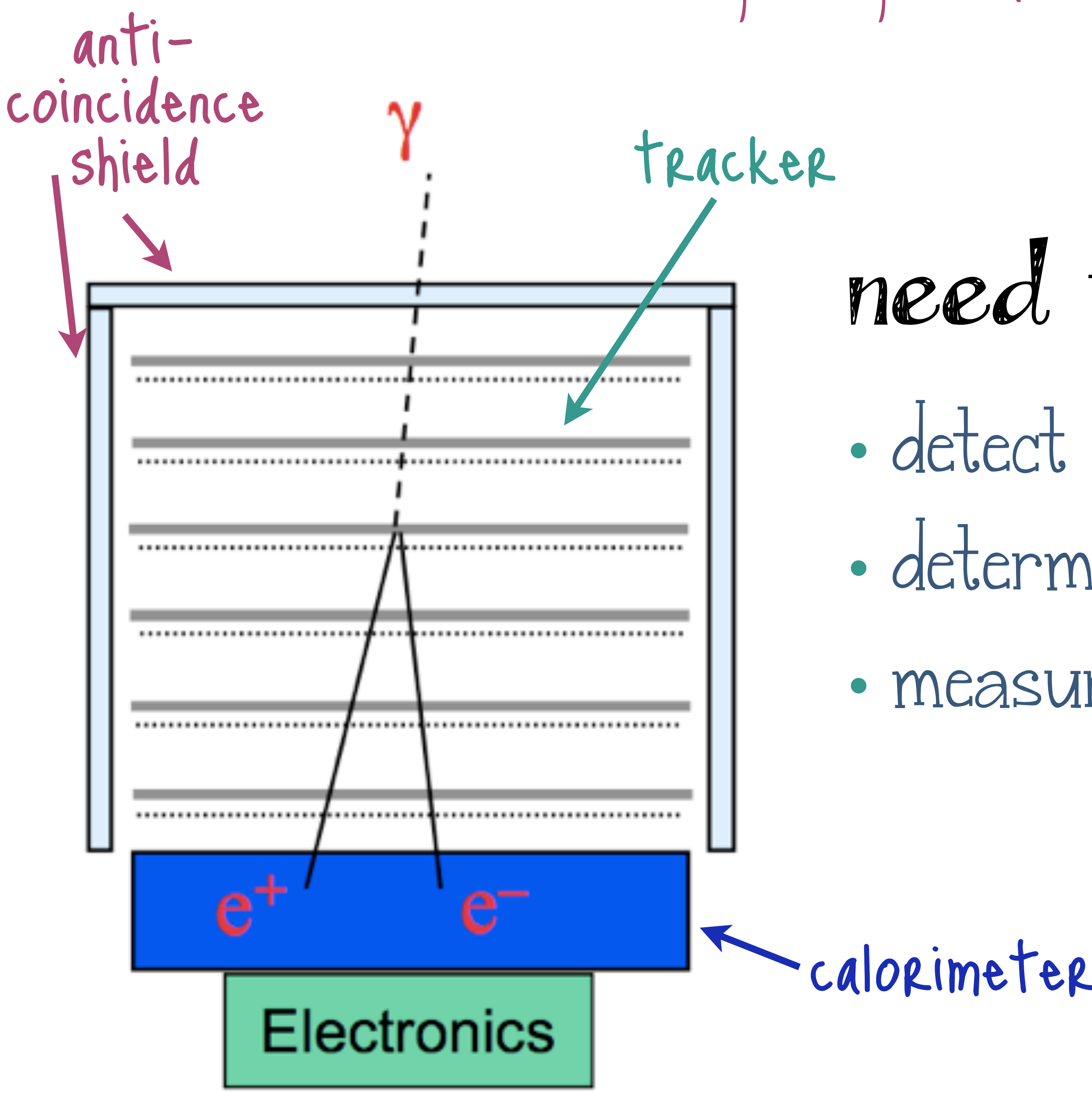
for

listening

deirdre@llr.in2p3.fr

HE Technique

Gamma ray interacts directly in detector
(pair produces)



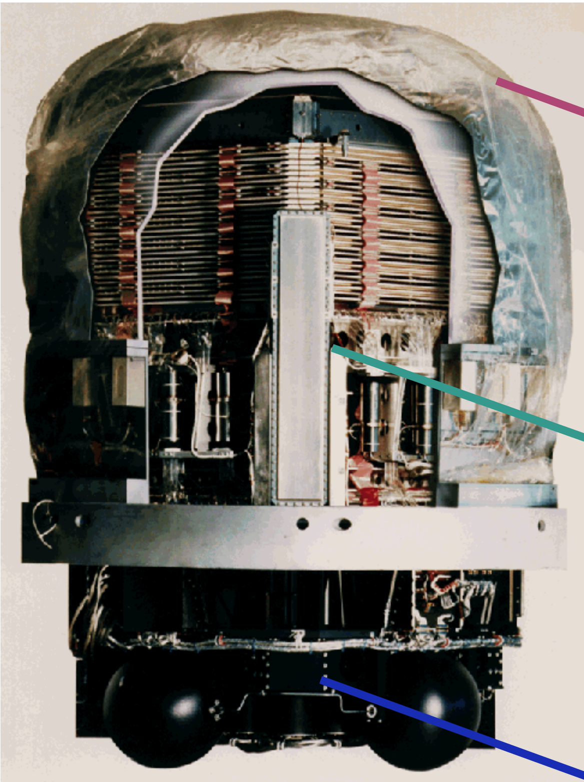
need to:

- detect gamma rays / reject background
- determine gamma-ray direction
- measure the energy of the gamma rays

PAIR PRODUCTION

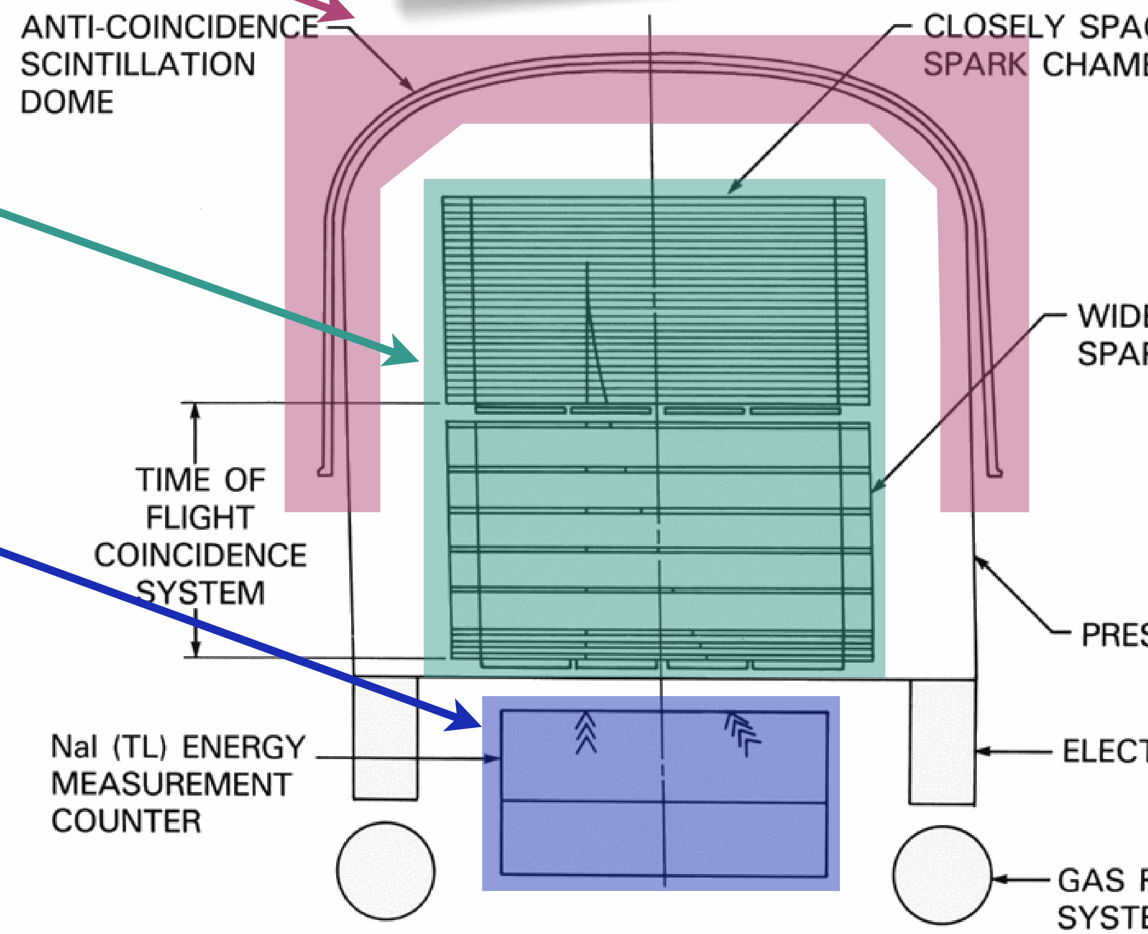
$$\gamma + \gamma^{*} \rightarrow e^{+} e^{-}$$

HE Technique

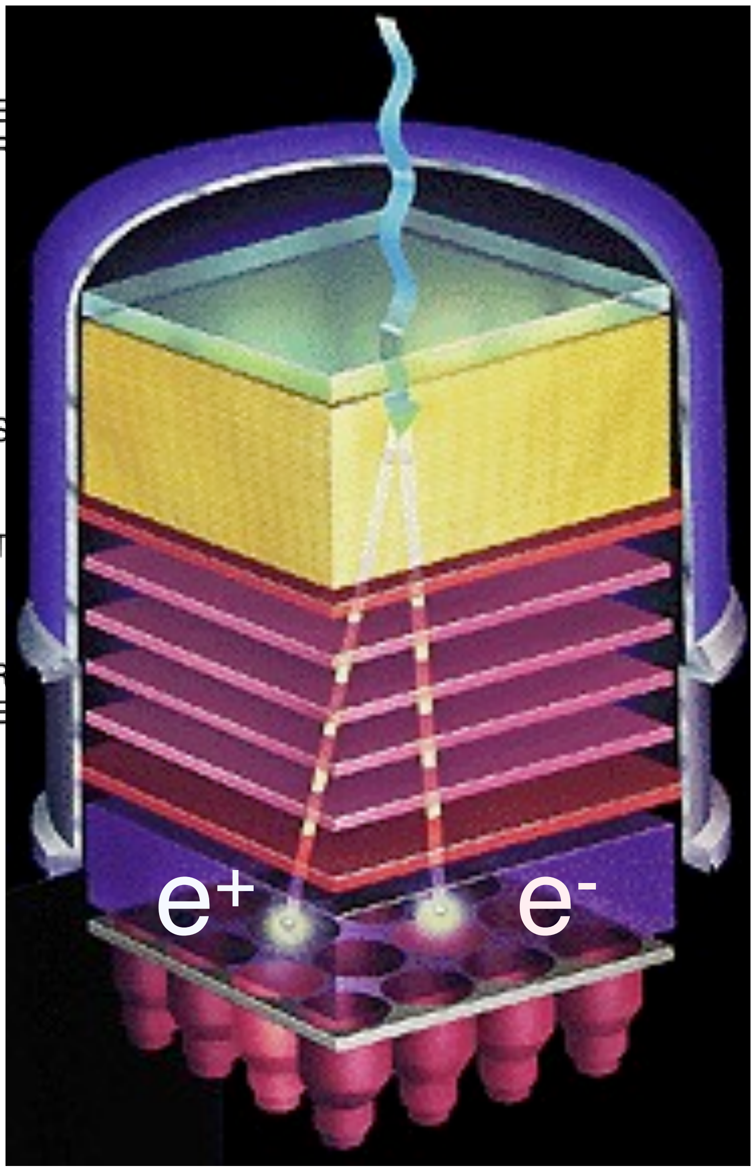


EGRET (1991 - 2000) energetic gamma ray experiment telescope

energy range: 20 MeV - 30 GeV



γ



anti-coincidence shield - plastic scintillator

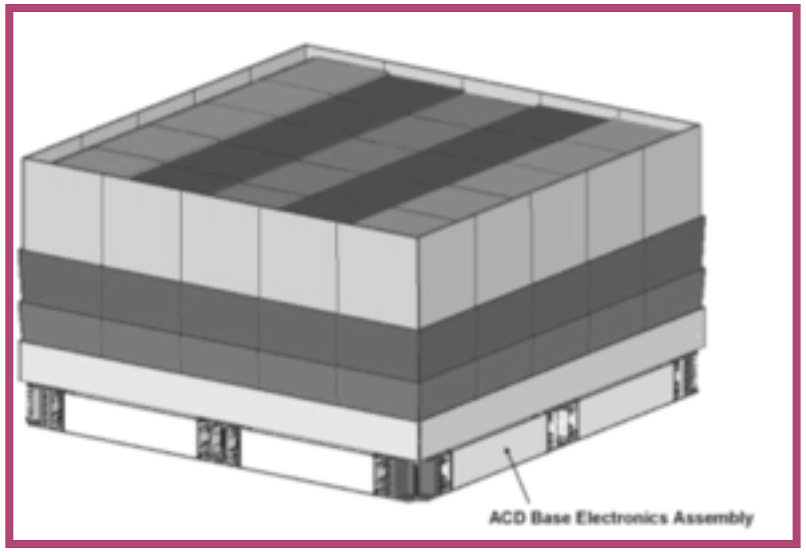
tracker - spark chambers

calorimeter - thallium-activated sodium iodide

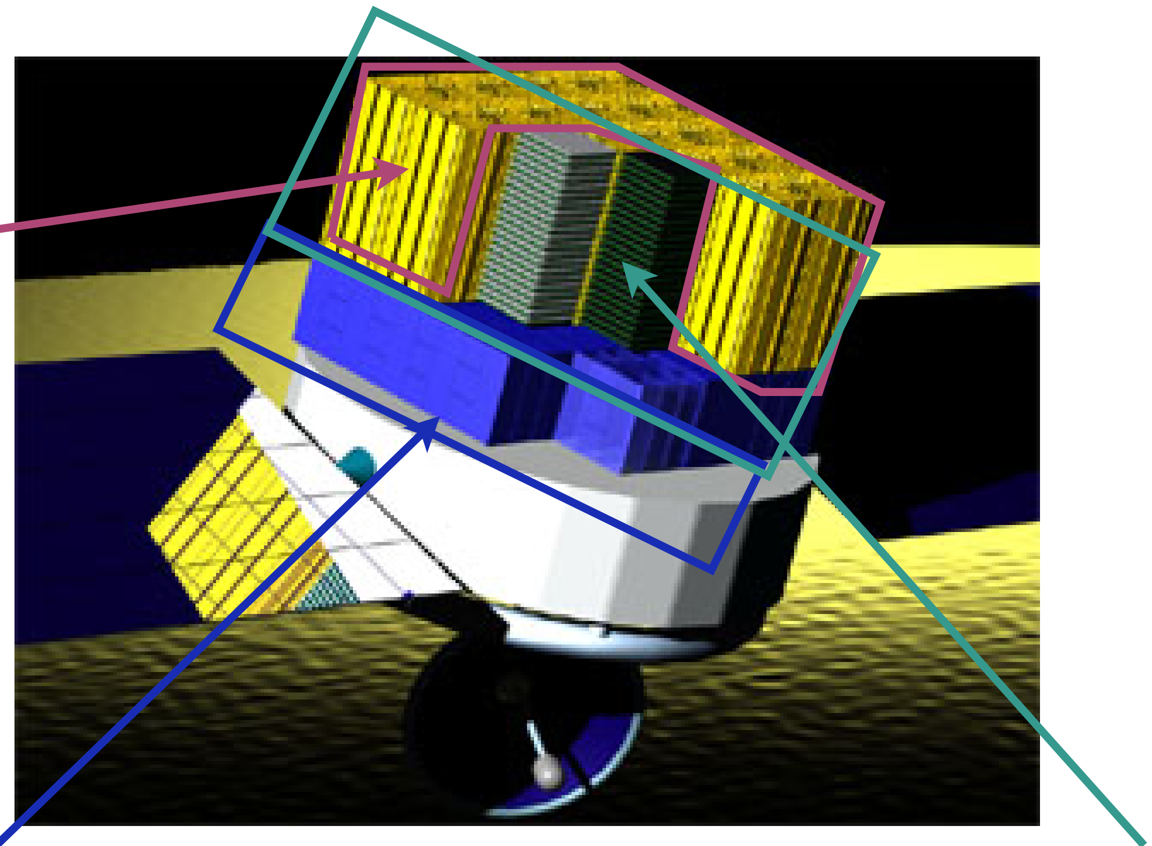
HE Technique

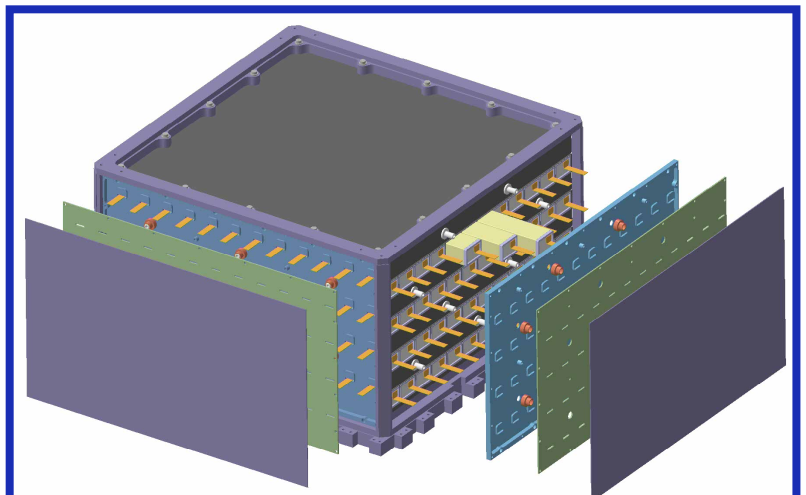
Fermi LAT (2008 ...) large area telescope

energy range: 20 MeV - 300 GeV

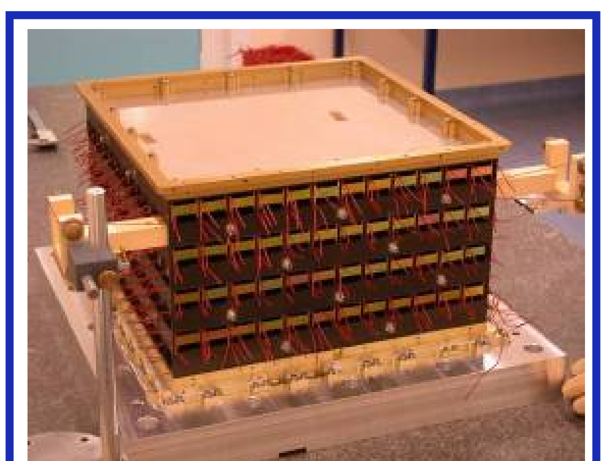


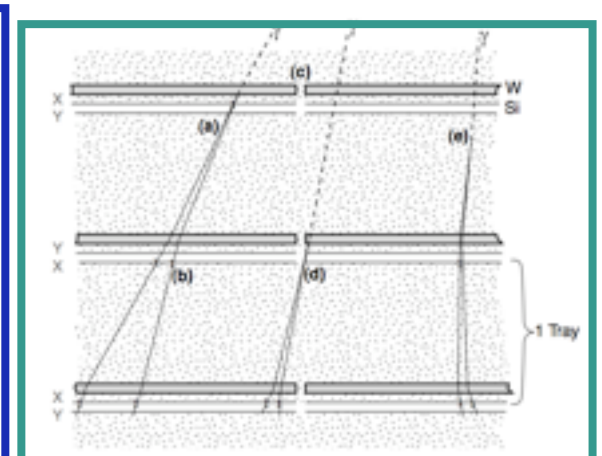
anti-coincidence shield - segmented





calorimeter - 1536 (16 x 96) crystals of CsI(Tl) - position and energy determination

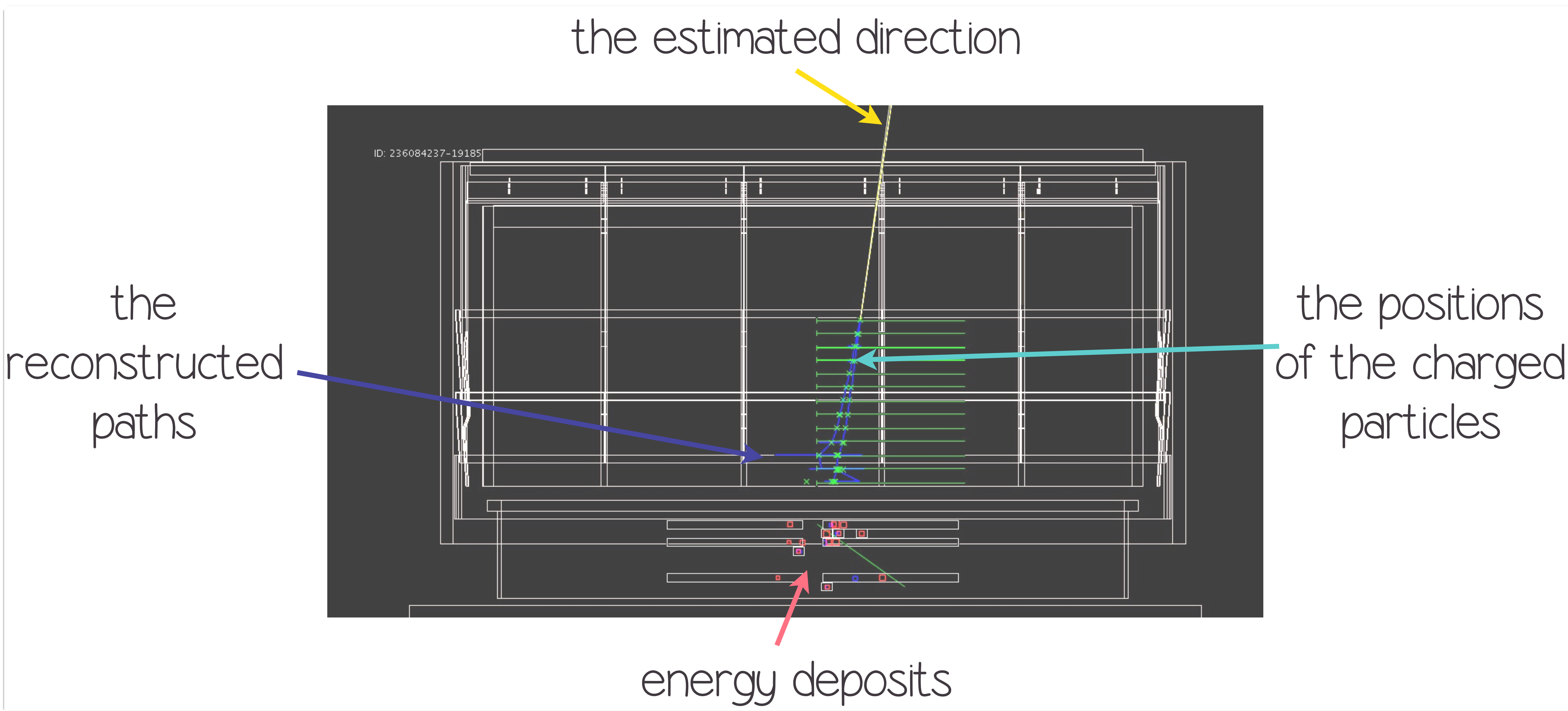




tracker - alternating layers of converter (tungsten) and detector (silicon strip)

HE Technique

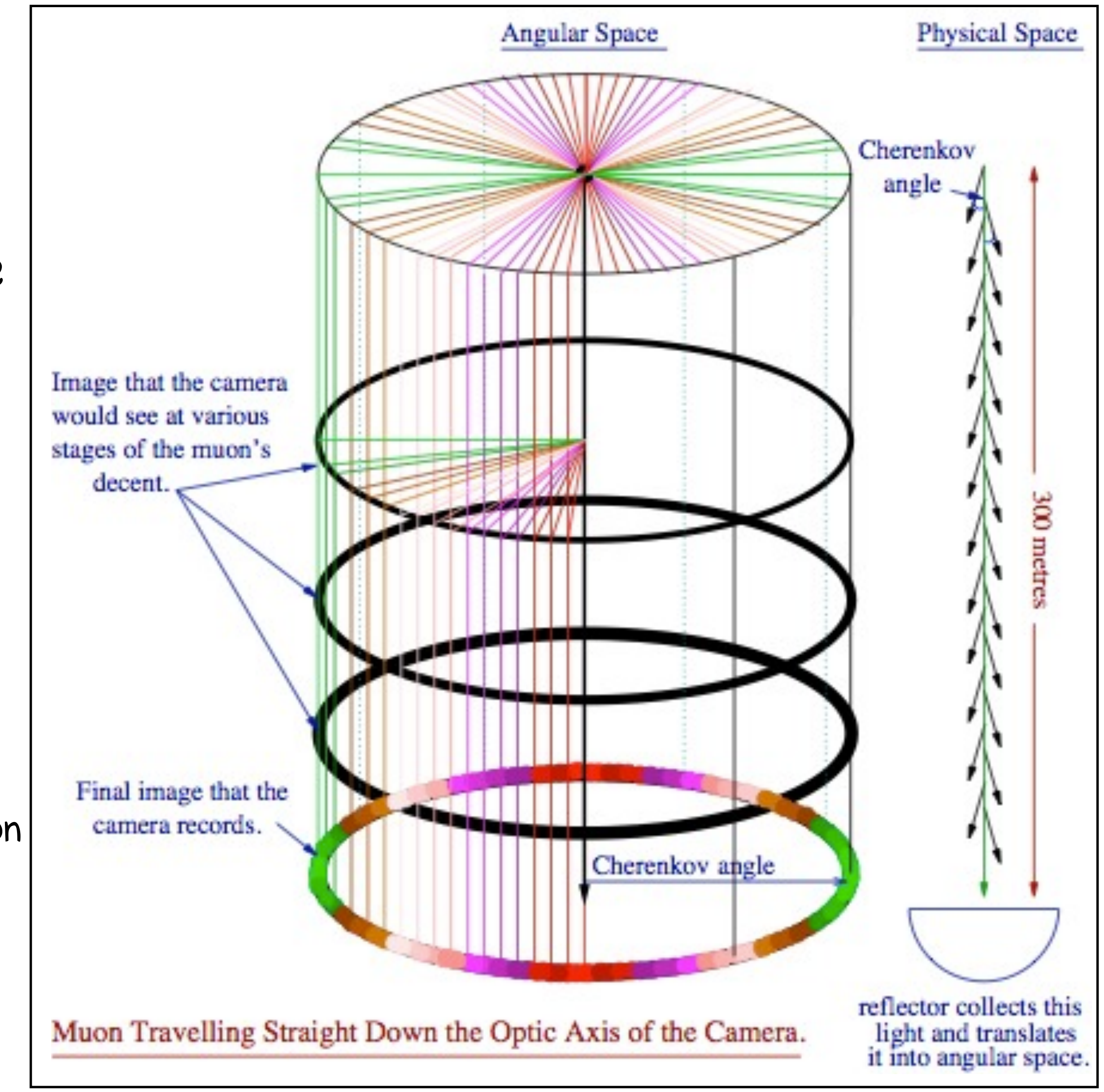
The three sub-detectors work together to reconstruct the e^+/e^- tracks and to estimate the energy of the primary particle



Muons

Muons (produced (mostly) in hadronic showers from pion decay)

- do not interact strongly with matter so a large proportion reach the earth's surface
  - ➡ the "penetrating component" of cosmic rays
- all Cherenkov photons induced by the muon are radiated at roughly the same angle -> cylindrical wave
  - ➡ **intensity falls off as 1/r where r is distance from the muon trajectory**
  - ➡ all of the light from the muon's ~300m trajectory is focused by the mirror onto the same ring-like image, strongly enhancing its intensity

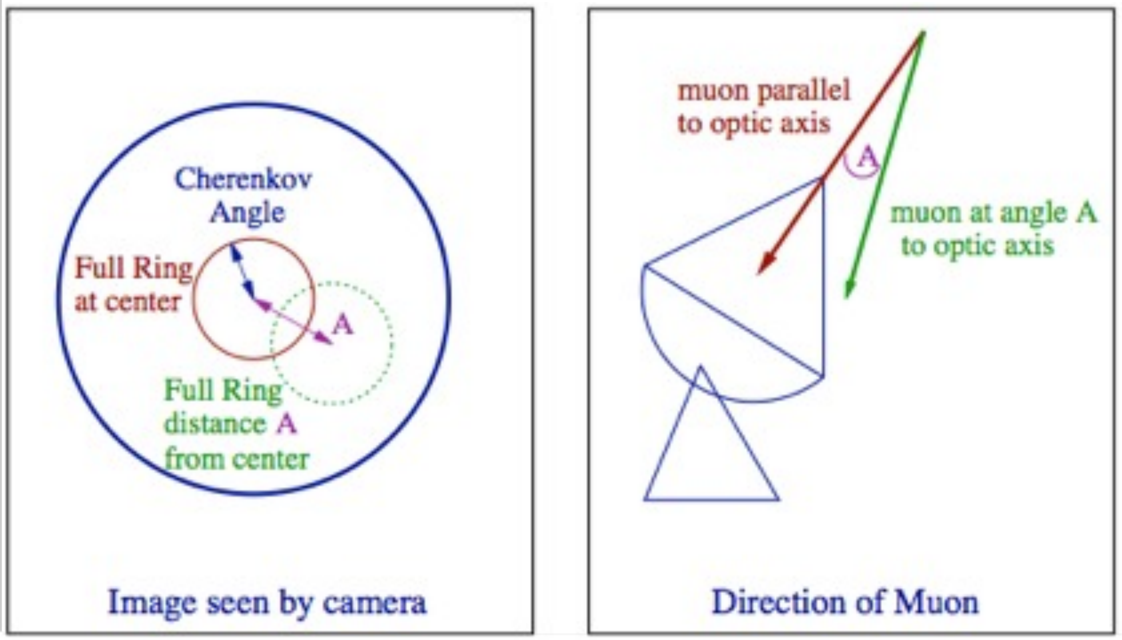


- like muons, e^-/e^+ induce cylindrical waves of Cherenkov radiation but the radiation lengths are short so each e^-/e^+ only radiates coherently for a very short path length and the net effect is that the Cherenkov radiation is diffuse
  - ➡ thus the Cherenkov radiation from a ~1TeV gamma-ray, which comprises about 100 radiating charged particles, has the form of a spherical wave with an intensity that falls off as $1/r^2$

Muons

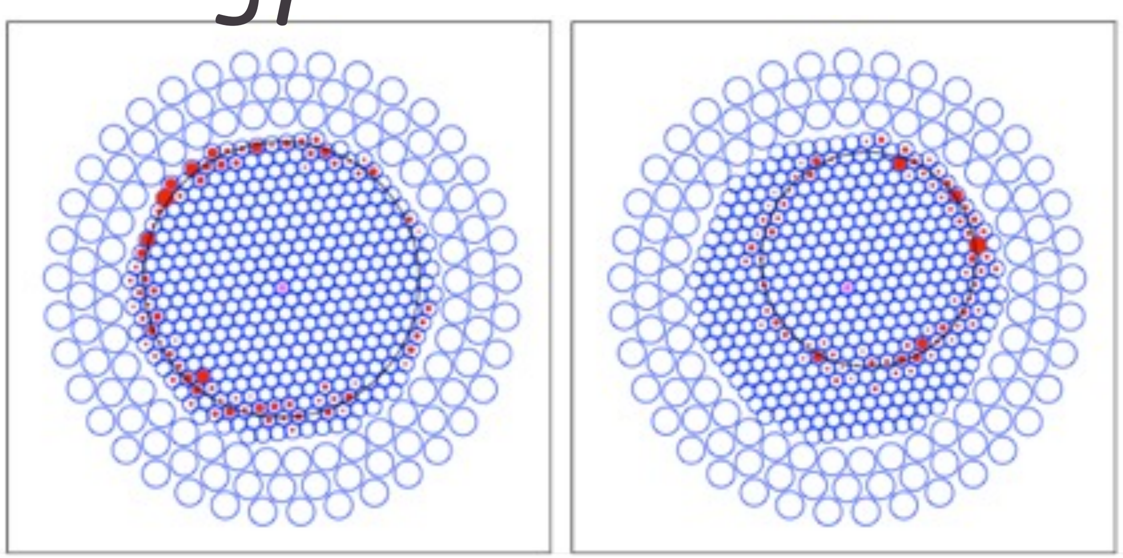
Muons in the camera*

Direction

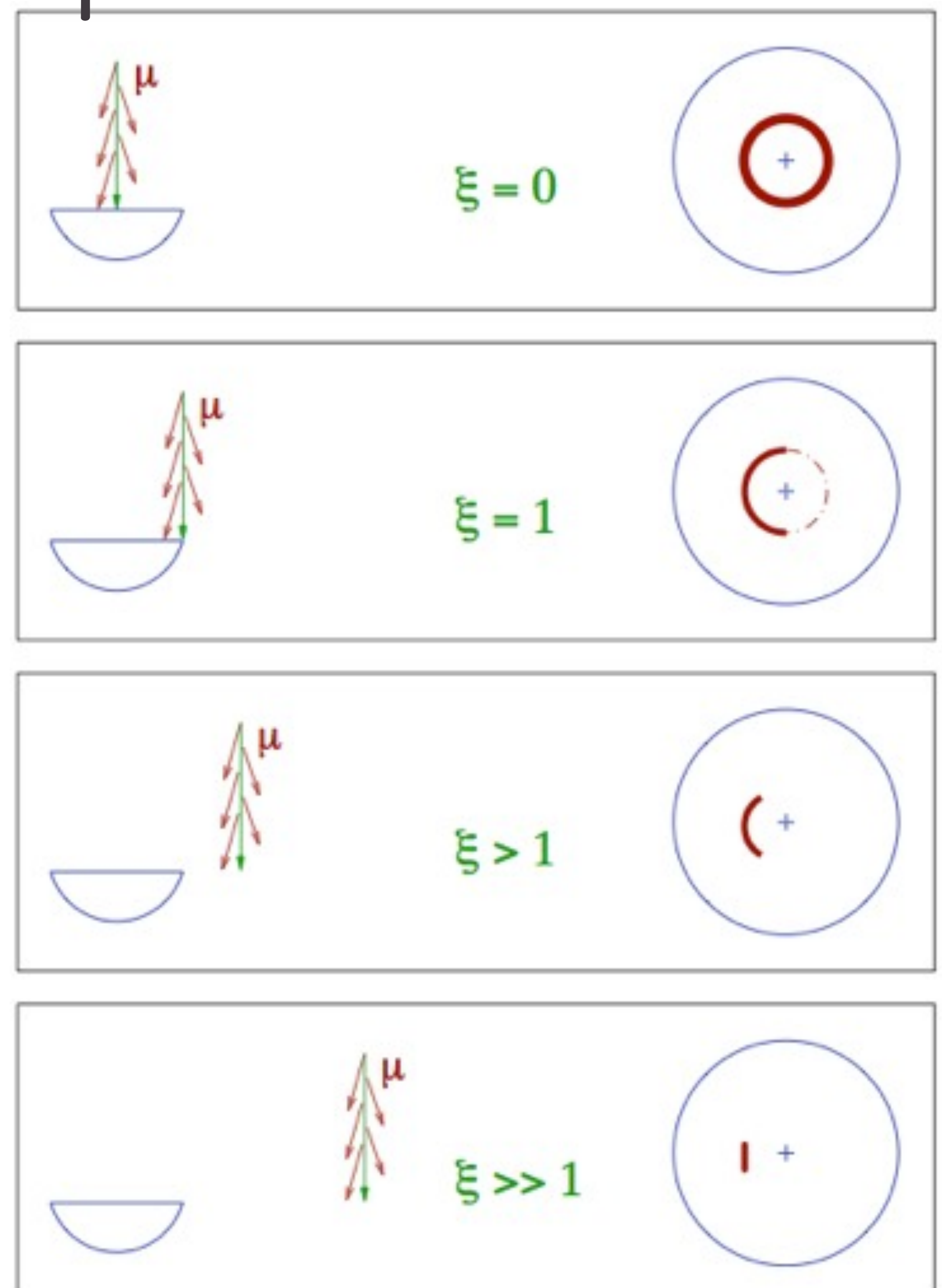


Energy

*radius=cherenkov angle

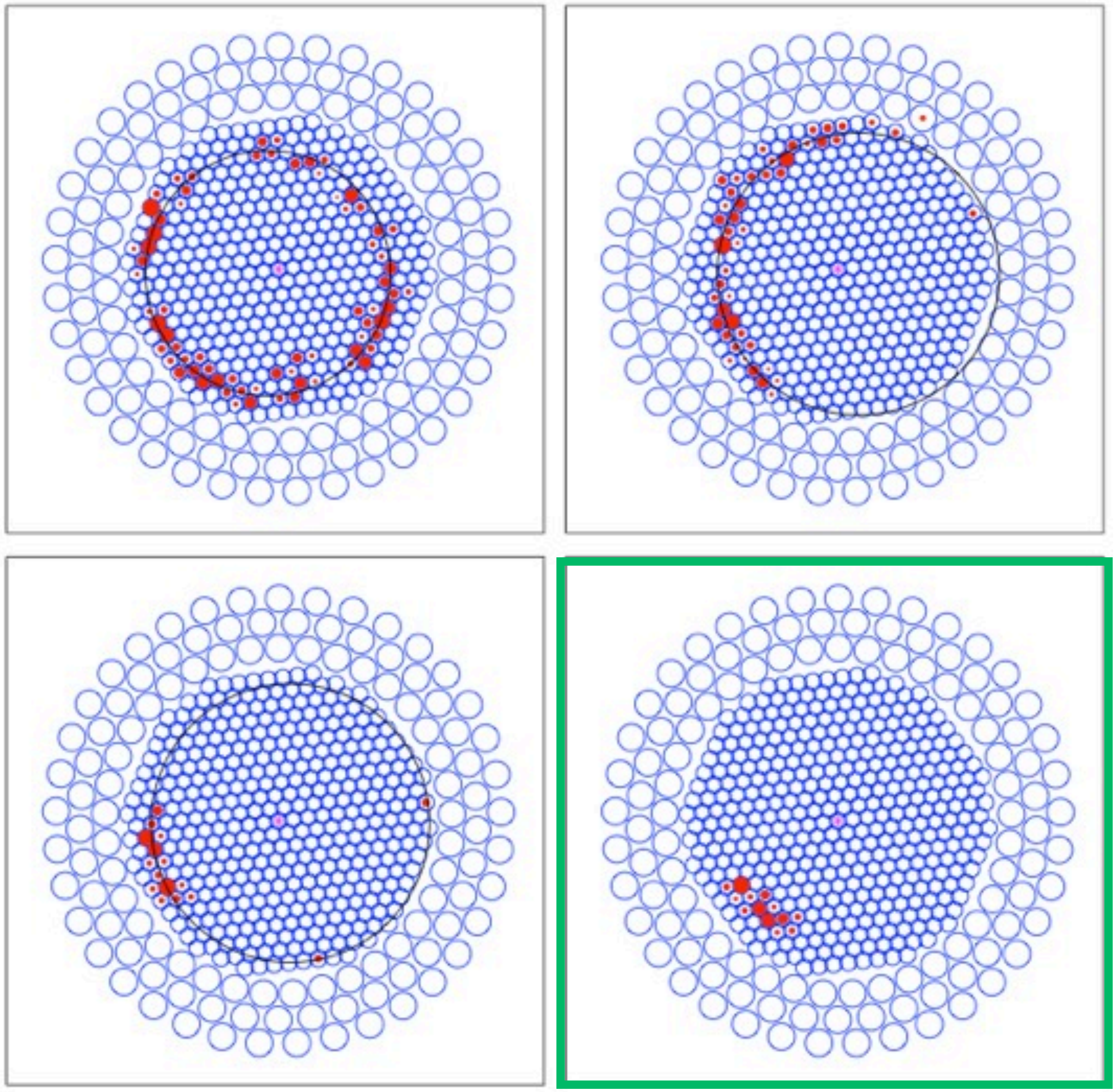


Impact Parameter

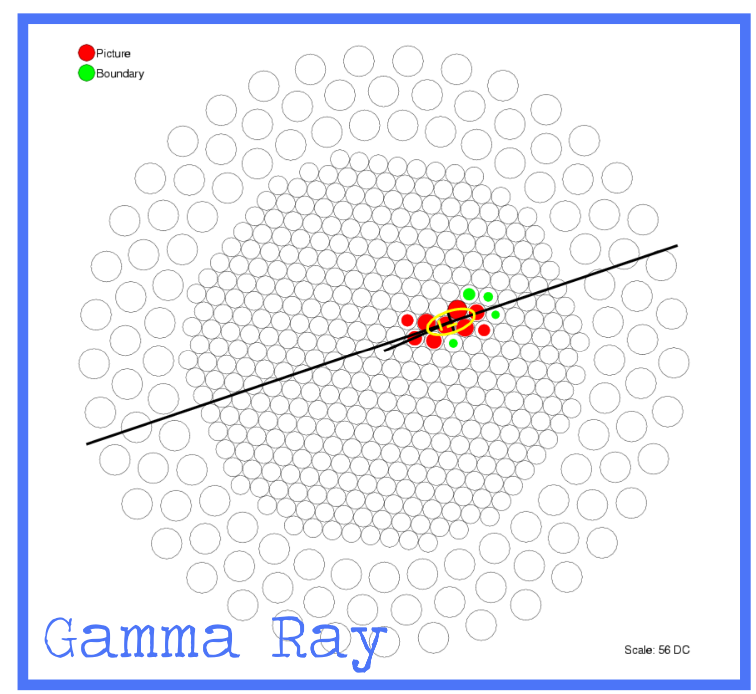


Muons

Real & simulated muons with different impact parameters



Cherenkov light from local muons is indistinguishable from a low-energy gamma-ray shower



or Partial Muon?